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A comparison of thinning methods in red pine: consequences for stand-level growth and tree diameter

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Abstract: Long-term replicated experiments that contrast thinning method (dominant thinning, thinning from below) while controlling stocking level are rare. Stand growth and tree size responses to thinning method can be useful for making decisions to achieve desired objectives, whether these are timber or wildlife habitat related. We examined data from two long-term (>50 year old) silvicultural experiments in red pine to understand how alternative thinning prescriptions influence stand-level basal area, volume, and biomass growth, as well as quadratic mean tree diameter. We found that gross growth in stands treated with dominant thinning was often, although not always, greater than growth in stands treated with thinning from below. However, the differences in growth between thinning methods are smallest at stocking levels and stand ages typical for red pine management. We found that biomass growth increases with dominant thinning were generally less than basal area or volume growth increase. Furthermore, greater gross growth associated with dominant thinning versus thinning from below must be weighed against the significantly smaller average tree sizes that result from repeated dominant thinning.

Résumé : Les suivis à long terme d'expériences répétées comparant des méthodes d'éclaircie (par le haut ou par le bas) tout en contrôlant la densité résiduelle sont rares. Les réactions en croissance du peuplement et des arbres individuels en fonction de la méthode d'éclaircie peuvent être utiles pour prendre les décisions qui permettent d'atteindre les objectifs visés, qu'ils soient reliés à la production de matière ligneuse ou aux habitats fauniques. Nous avons analysé les données de deux expériences sylvicoles de longue durée (plus de 50 ans) dans des peuplements de pin rouge pour comprendre comment différentes prescriptions d'éclaircie influencent la surface terrière, le volume, la croissance en biomasse du peuplement de même que le diamètre moyen quadratique des arbres. Nous avons trouvé que l'accroissement brut des peuplements éclaircis par le haut était souvent, mais pas toujours, plus grand que celui des peuplements éclaircis par le bas. Cependant, les différences de croissance entre les méthodes d'éclaircie étaient plus petites à des densités et des âges typiques de l'aménagement du pin rouge. Nous avons trouvé que l'augmentation de la croissance en biomasse à la suite d'une éclaircie par le haut était généralement inférieure aux augmentations de croissance en surface terrière ou en volume. De plus, on doit mettre en balance l'accroissement brut plus élevé associé à l'éclaircie par le haut comparativement à l'éclaircie par le bas et la taille moyenne significativement plus petite des arbres à la suite d'éclaircies répétées par le haut.

[Traduit par la Rédaction]

Introduction

Thinning of a forest stand is an important tool to achieve a variety of management objectives. Traditionally, thinning has been used as a tool to capture anticipated mortality of suppressed trees as marketable wood (Drew and Flewelling 1979) and to increase the growth of residual trees by increasing growing space and resource availability to these trees (Smith et al. 1997). Thinning can also be used to develop structural characteristics important for wildlife habitat and to direct the development of structural complexity in simplified stands (Franklin et al. 1986, 1997; Hayes et al. 1997). For example, thinning can be used to promote the development of large diameter trees, which can be important as roosting and nesting sites, as the location of large dens and cavities, and ultimately, as a source of large woody debris. Likewise, thinning can be used to promote other structural characteristics, including the development of forest understories and vertical structure (Bailey and Tappeiner 1998; Miller and Emmingham 2001).

Thinning can be applied in various ways to a stand, depending on the crown position of the trees removed (Nyland 1996; Smith et al. 1997; Helms 1998). Dominant thinning (previously referred to as selection thinning) preferentially removes the largest diameter, usually dominant crown class, trees (Helms 1998). In contrast, crown thinning, synonomous with thinning from above (Helms 1998), removes dominant and codominant trees specifically to increase the

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Table 1. Allometric equations for estimation of stem volume and aboveground biomass from diameter and height measurements.

Component	Equation*	Source†
Stem volume	$V = 0.003\ D_{in}{}^{1.79}\ H_{ft}{}^{1.12}$	Fowler 1997
Bole biomass	$\ln(B_{kg}) = -2.84 + 2.39\ \ln(D_{cm})$	Ker 1980
Branch biomass	$\ln(B_{lb}) = -1.51 + 2.50\ \ln(D_{in})$	Young et al. 1980
Foliar biomass	$\ln(B_{lb}) = -1.21 + 2.18\ \ln(D_{in})$	Young et al. 1980

*Similar equations for other species were used, and are available in Jenkins et al. (2004). V is stem volume in cubic feet; B_{kg} and B_{lb} are biomass in kilograms and pounds, respectively; D_{cm} and D_{in} are diameter at breast height in centimetres and inches, respectively; and H_{ft} is height in feet. Values were converted to metric units for analysis.

†Ker (1980) and Young et al. (1980) were both compiled in Jenkins et al. (2004).

growing space of healthy residual trees within the same crown classes (Smith et al. 1997) but does not necessarily remove the largest diameter trees preferentially. Thinning from below, or low thinning, removes trees from the small end of the diameter distribution, usually suppressed, intermediate, or small codominant trees (Helms 1998).

Thinning, and how it is applied, can influence a variety of stand characteristics, including gross growth, production of stem wood, and the maximum, mean, and range of tree diameters. Most empirical studies have found that generally, in single-cohort, largely single-species stands, volume and basal area growth on an area basis tend to be similar regardless of thinning method if other factors are constant, e.g., basal area of growing stock, site index, and vigor of residual trees (Spur et al. 1957, low vs. crown thinning; Cooley 1969, low vs. dominant vs. crown thinning; Seidel 1986, low vs. dominant thinning; Smith 2003, low vs. dominant vs. crown thinning; Gilmore et al. 2005, low vs. dominant thinning). Some studies report higher volume growth with thinning from below, but it is not clear if basal area of growing stock was similar between treatments (Emmingham et al. 2007, low vs. crown thinning). One recent study in mature red pine (*Pinus resinosa* Aiton) suggests that dominant thinning results in greater gross basal area growth relative to low thinning (Buckman et al. 2006).

Thinning method can influence stand diameter distributions. By removing smaller diameter trees, low thinning shifts the diameter distribution and the mean tree diameter towards larger trees. Dominant thinning, on the other hand, shifts the distribution and mean diameter towards smaller trees.

While informative, many studies are limited by experimental design (e.g., lack of replication), lack of long-term data and (or) temporal analysis, or a focus on only one growth variable (e.g., basal area). In fact, as Smith (2003) points out, there are few published studies of long-term replicated thinning method experiments, in particular those that hold residual basal area constant, that can be used to address issues of thinning responses in detail.

In this study, we explore how thinning method influences periodic growth (basal area, volume, biomass) and tree diameter, using data from two long-term replicated studies in red pine. An analysis of these studies was included as part of a recent comprehensive Forest Service Technical report on growth and yield in red pine (Buckman et al. 2006). Our intention is to explore growth responses in more detail (e.g., multiple measures of growth over time). Specifically, our objectives were to (1) quantify the overall influence of thinning method, stocking level, and stand age on basal area growth, stem volume growth, biomass growth, and mean tree diameter, and (2) assess how the magnitude of the impact of thinning method depends on stand age and stocking level.

Methods

Study sites and treatments

We examined growth records from two long-term red pine silvicultural experiments in Minnesota: the Birch Lake cutting method – growing stock study and the Cutfoot cutting methods study. The Birch Lake experiment is located at the Superior National Forest in northeastern Minnesota. Stands are of plantation origin (seeded) and were established between 1912 and 1913. The Cutfoot experiment is located at the Chippewa National Forest, Cutfoot Experimental Forest, in north-central Minnesota, and stands were naturally regenerated around 1870. Species composition at both sites is dominated by red pine, which comprises over 95% of basal area throughout the experiments. Eastern white pine (*Pinus strobus* L.) and jack pine (*Pinus banksiana* Lamb.) are the bulk of the remaining trees, with other species making up less than 1% of basal area.

Both experiments contrasted dominant thinning to thinning from below (Buckman et al. 2006). Specifically, dominant and codominant trees of the largest diameters were removed preferentially (R. Buckman personal communication, 2007). However, it is useful to consider the effects of the dominant thinnings on crown distributions and tree diameters. In both studies, the ratio of the mean diameter of trees before and after the first thinning ranged from 1.0 to 1.2 (Buckman et al. 2006), suggesting that mean diameters were little affected by thinning. This reflects the fact that in managed red pine stands, most crowns are in dominant and codominant positions, with the proportion of suppressed and intermediate crown classes constituting a small percentage of a stand (Buckman et al. 2006). In effect, the dominant thinning method used in these studies was operationally a crown thinning, despite being implemented conceptually (and referred to here) as a dominant thinning.

At Birch Lake, the thinning method was applied to five levels of residual growing stock (7, 14, 21, 28, and 34 $m^2 \cdot ha^{-1}$). Treatment combinations were assigned randomly to 0.8 ha stands, each randomly divided into three thinning methods (dominant and below, both included in this analysis, and intermediate, which is not addressed in this paper). Each thinning treatment was replicated three times in a completely randomized design. At Cutfoot, a single level of residual growing stock was used (~ 25 m^2·ha^{-1}). Thinning treatment was assigned randomly to 4.0 ha stands, with three replicates of each treatment. An unthinned control (not examined here) was included only in the Birch Lake experiment.

Both experiments were thinned at 5–10 year intervals from about the origination cut until 2003 (Birch Lake) and 2005 (Cutfoot). Cutfoot stands were established (initial thinning) in 1950 and subsequently thinned in 1960, 1970, 1985, and 2005. Birch Lake stands were established (initial thinning) in 1957 and subsequently thinned in 1962, 1972, 1982, 1992, and 2003, with the exception of the lowest two residual basal area treatments whose basal area was sufficiently low that they were not thinned after 1962. Following the initial thinning, volume removed by harvest did not differ between thinning methods and averaged 45 m^3·ha^{-1} and 48 m^3·ha^{-1} at Birch Lake and Cutfoot, respectively. Stands were measured immediately before each thinning on a single (Birch Lake) or 10 (Cutfoot) permanent 0.8 ha plots per stand. Measurements included diameter at breast height (DBH = 1.37 m) for all trees with DBH >10 cm, and height for 2–3 trees in each crown class in each plot, with the latter assessed in the field based on visual determination of crown exposure.

Analysis

We assessed growth and diameter responses to thinning methods. Growth measures consisted of gross basal area, stem volume, and whole-tree (bole, branch, and foliage) aboveground biomass for all red, white, and jack pines with DBH >10 cm. Gross growth estimates for each variable were defined as accretion (i.e., growth on existing trees), ingrowth of new trees, and amounts removed in harvest and mortality. We used gross growth instead of net growth, as the former is more biologically representative of stand productivity and is less affected by mortality (Curtis and Marshall 1988). Moreover, in these studies, gross and net growth differed little because average annual mortality was less than 0.15% of basal area, volume, or biomass. We measured heights from a subsample of trees in each stand at each measurement period, related height to DBH (results not shown, r^2 values between 0.4 and 0.8), and used these results to estimate unmeasured heights. Since tree heights within even-aged red pine stands are quite consistent (Buckman et al. 2006), height variation in individual trees that is not captured in our regression equations is quite minor. Stem volume and aboveground biomass were estimated from DBH and height using allometric equations (Table 1). In addition, at each measurement period, we calculated quadratic mean diameter (QMD) by plot from diameter measurements (d) for trees i = 1 through n (Husch et al. 2003) as

$$\mathrm{QMD} = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}}$$

QMD was used rather than arithmetic mean diameter, as the former provides a better mensurational representation of average tree size differences among treatments (Curtis and Marshall 2000).

To assess the influence of thinning method on stand growth (objective 1), we used repeated measures analysis of variance, with thinning method, residual basal area, and stand age as class variables, with age as a repeated measure, with plot as a random variable, and with basal area growth, stem volume growth, biomass growth, or QMD as dependent variables. We conducted mean contrasts as appropriate to identify significant differences between thinning methods within interactions. We indicate differences that are significant at the $\alpha = 0.05$ level (see Fig. 1 for illustration of contrasts). Statistical analysis was performed using the MIXED procedure in SAS version 9.1 (SAS 2001) with autoregressive covariance structures for models with homogeneous residuals and with autoregressive heterogeneous covariance structures for models with nonhomogeneous residuals. To characterize the consequences of dominant thinning versus thinning from below (objective 2), we calculated the relative difference between thinning method using the formula $(D - B)/D$, where D is response with dominant thinning and B is response to thinning from below. This formula quantifies the percentage increase or decrease in growth or diameter as a consequence of dominant thinning compared with thinning from below and was calculated for all treatments for basal area growth, volume growth, biomass growth, and QMD.

Results

At Cutfoot, basal area growth ranged from 0.29 to 0.66 m^2·ha^{-1}·year^{-1}, stem volume growth ranged from 4.55 to 6.8 m^3·ha^{-1}·year^{-1}, while biomass growth ranged from 1.49 to 2.9 Mg·ha^{-1}·year^{-1} (Table 2). All three measures of growth were significantly related to thinning method, while basal area and biomass growth were also related to stand age (Table 2). The interaction of stand age and thinning method was not significantly related to any of the three growth variables at Cutfoot. These models explained 81% and 72% of the variability in basal area and biomass growth, respectively, while thinning method alone explained 45% of the variability in stem volume growth (Table 2). QMD at Cutfoot ranged from 23 to 45 cm, and 95% of the variability in QMD was explained by statistically significant relationships with stand age, thinning method, and the interaction of age and thinning method (Table 2). Basal area growth and biomass growth decreased with age at Cutfoot, while QMD increased with age, and volume growth was statistically consistent across all ages (Fig. 1).

Dominant thinning generally resulted in higher growth and smaller diameters at Cutfoot. Both basal area growth and biomass growth were significantly higher with dominant thinning at all ages except for the youngest measurement period. Volume growth at Cutfoot was significantly greater with dominant thinning only at 120 years. For QMD, the interaction of age and thinning method at Cutfoot suggests that differences between thinning methods depend on age, although QMD was significantly larger with thinning from below across all ages (Fig. 1). Relative to thinning from below, dominant thinning at Cutfoot increased basal area, volume, and biomass growth by an average of 43%, 21%, and 31%, respectively, and decreased QMD by an average of

Fig. 1. Basal area growth (m²·ha⁻¹·year⁻¹), stem volume growth (m³·ha⁻¹·year⁻¹), aboveground biomass growth (Mg·ha⁻¹·year⁻¹), and quadratic mean diameter (cm) in long-term red pine experiments as a function of thinning method, stand age, and residual basal area. Asterisks indicate significant differences between dominant thinning and thinning from below at that level of age and residual basal area; all other differences between thinning methods are not significant at α = 0.05. Error bars are ± one standard error.

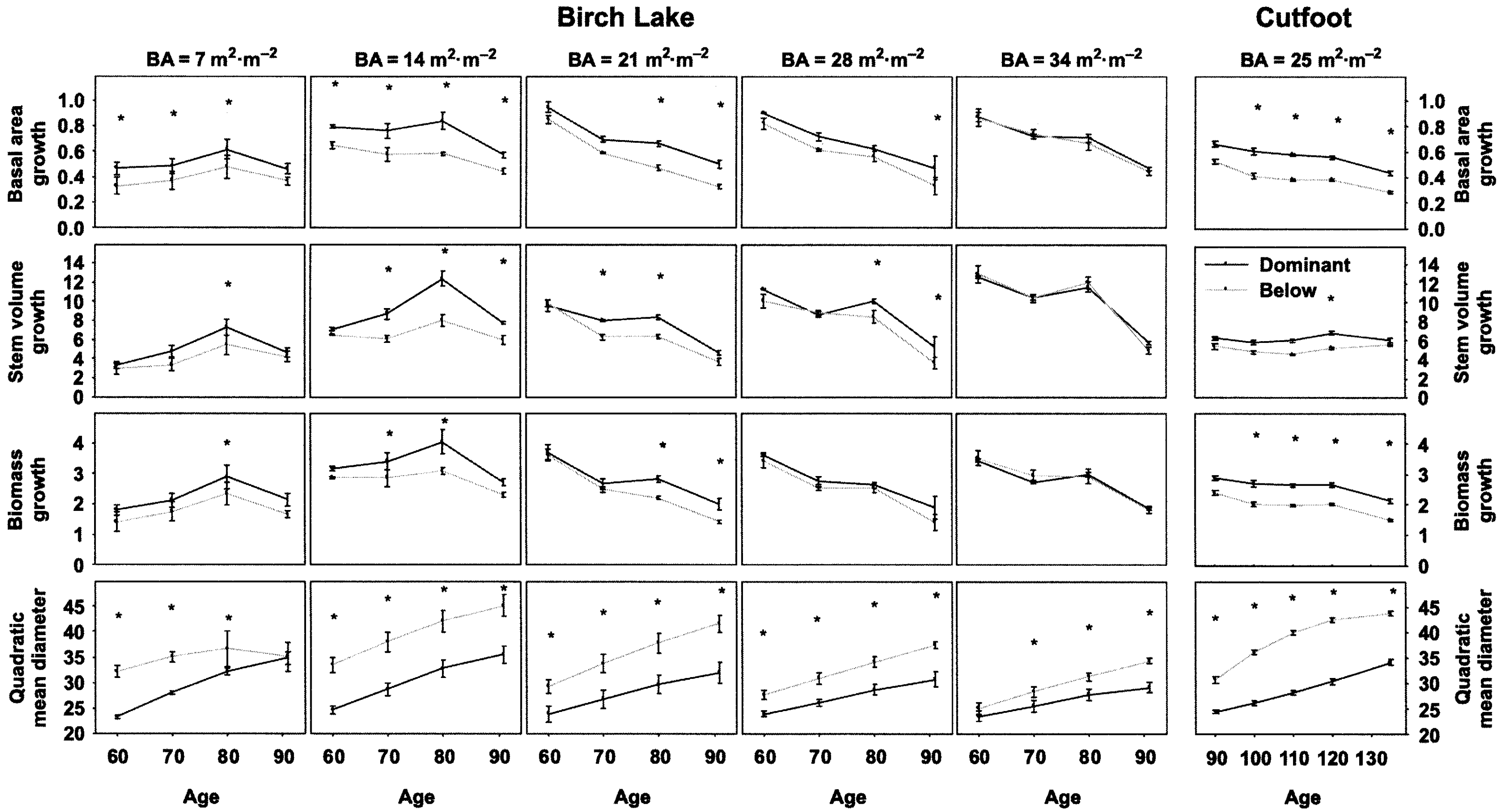

Table 2. Analysis of variance results for basal area growth, stem volume growth, and biomass growth in stands thinned using dominant thinning and thinning from below across a range of residual basal areas and stand ages.

		Basal area[a]			Stem volume[b]			Biomass[c]			Quadratic mean diameter[d]		
Source	df	Sum of squares	*F* stat	*P* value	Sum of squares	*F* stat	*P* value	Sum of squares	*F* stat	*P* value	Sum of squares	*F* stat	*P* value
Birch Lake													
Method	1	6.99	47.8	<0.001	7 699	29.2	<0.001	489 130	21.3	<0.001	171	134.3	<0.001
Basal area	4	15.93	12.1	<0.001	81 490	59.5	<0.001	2 307 151	8.63	0.003	102	4.8	0.020
Basal area × method	4	1.81	3.1	0.620	3 287	3.12	0.066	202 736	2.2	0.137	20	4.0	0.027
Age	3	28.00	119.8	<0.001	59 290	205.8	<0.001	3 649 593	112.5	<0.001	209	193	<0.001
Age × method	3	0.18	0.86	0.466	1 861	4.96	0.004	69 014	1.62	0.195	0.3	0.4	0.748
Basal area × age	12	13.35	12.1	<0.001	44 322	24.9	<0.001	2 529 971	14.6	<0.001	7.8	2.3	0.019
Basal area × age × method	12	0.50	0.67	0.768	2 806	2.39	0.014	83 128	0.69	0.755	14	3.6	<0.001
Model	39	66.76	15.2	<0.001	200 755	31.5	<0.001	9 330 723	11.7	<0.001	523	13.1	<0.001
Error	80	9.02			13 081			1 633 482			82		
Total	119	75.77			213 836			10 964 205			605		
Cutfoot													
Method	1	4.2	26.2	0.005	1 802	7.2	0.041	466 745	19.2	0.004	1153	58.0	0.002
Age	4	3.2	14.9	0.003	545	1.1	0.402	346 444	6.0	0.004	741	43.1	<0.001
Age × method	4	0.1	0.6	0.694	230	0.5	0.769	6 592.97	0.1	0.974	51	6.1	0.004
Model	9	7.5	9.2	<0.001	2 577	1.8	0.123	819 782	5.7	<0.001	194	47.1	<0.001
Error	20	1.8			3 113			319 808			9.2		
Total	29	9.3			5 690			1 139 590			203.67		

Note: Independent variables include residual basal area at Birch Lake as well as thinning method and stand age at both Birch Lake and Cutfoot.

[a] r^2 = 0.88 for Birch Lake, r^2 = 0.81 for Cutfoot.

[b] r^2 = 0.94 for Birch Lake, r^2 = 0.45 for Cutfoot.

[c] r^2 = 0.83 for Birch Lake, r^2 = 0.72 for Cutfoot.

[d] r^2 = 0.86 for Birch Lake, r^2 = 0.95 for Cutfoot.

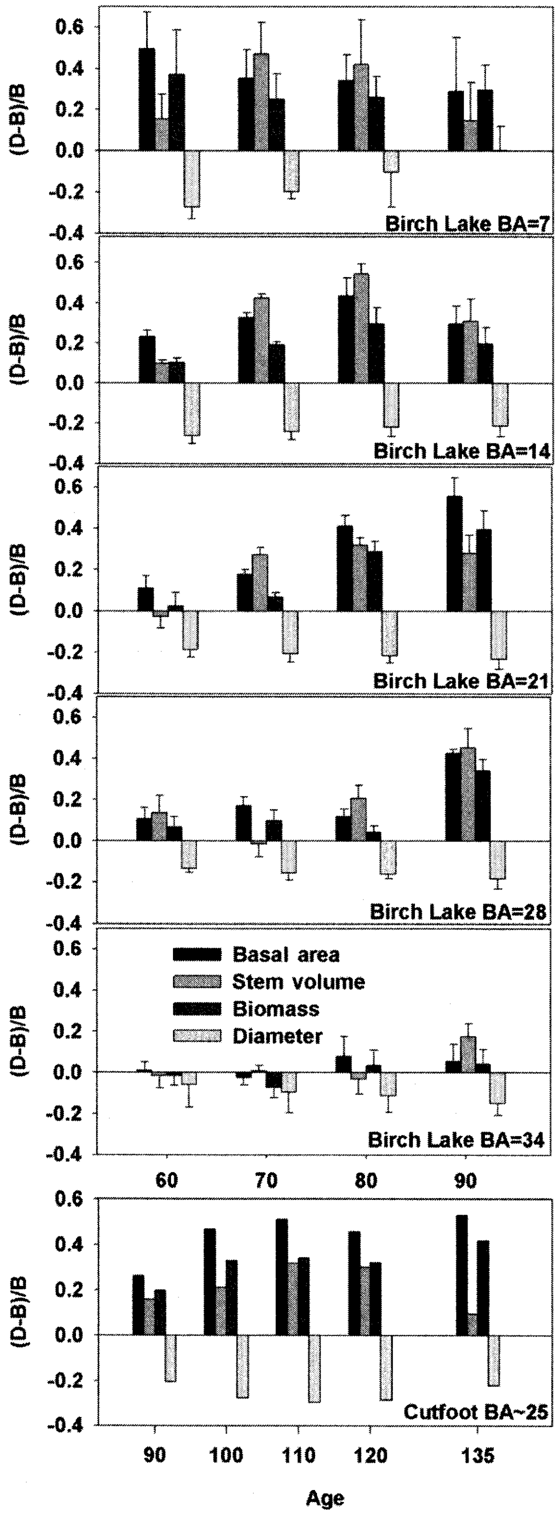

Fig. 2. Proportional difference in basal area growth, stem volume growth, biomass growth, and quadratic mean diameter of stands thinned by dominant thinning as opposed to stands thinned from below in long-term red pine studies at Birch Lake Plantation and Cutfoot Experimental Forest. Values are the percentage of higher or lower growth and larger or smaller diameters when dominant thinned compared with thinned from below. Error bars are ± one standard error.

26% (Fig. 2). The effects of dominant thinning on volume growth and QMD at Cutfoot were most pronounced at older stand ages (100–110 years), while the effects on basal area and biomass growth were relatively consistent across all ages greater than 90 years.

At Birch Lake, basal area growth ranged from 0.32 to 0.95 $m^2 \cdot ha^{-1} \cdot year^{-1}$, stem volume growth ranged from 3.0 to 12.9 $m^3 \cdot ha^{-1} \cdot year^{-1}$, and biomass growth ranged from 1.4 to 4.04 $Mg \cdot ha^{-1} \cdot year^{-1}$. All three growth variables at Birch Lake were influenced by thinning method, basal area, age, and the interaction of basal area and age (Table 2). In addition, stem volume growth was influenced by the interaction of thinning method and age and by the three-way interaction of thinning method, basal area, and age. These models accounted for 88%, 94%, and 83% of the variability in basal area growth, volume growth, and biomass growth, respectively. QMD at Birch Lake ranged between 23 and 45 cm, and 95% of the variability in QMD was accounted for by relationships with thinning method; basal area; age; the basal area and thinning interaction; the basal area and age interaction; and the three-way interaction of basal area, age, and thinning method.

These significant interactions indicate that the influence of thinning method (i.e., differences between dominant thinning and thinning from below) is best understood by examining all levels of both residual basal area and age (Fig. 1). Basal area growth tended to be significantly different under a wider range of conditions than stem volume growth and biomass growth, and significant differences were generally most frequent at intermediate levels of residual basal area (14–21 $m^2 \cdot m^{-2}$). QMD, on the other hand, was significantly higher with thinning from below under all conditions except the latest two measurement periods in the lowest residual basal area treatment and the earliest measurement period in the highest residual basal area treatment (Fig. 1). At Birch Lake, dominant thinning increased basal area, stem volume, and biomass growth by an average of 25%, 22%, and 16%, respectively, over thinning from below, whereas QMD decreased by an average of 15% (Fig. 2). The largest differences occurred in either younger stands (<70 years) with very low growing stock (7 $m^2 \cdot ha^{-1}$) or older stands (>80 years) with intermediate growing stock (14–28 $m^2 \cdot ha^{-1}$). Relative to thinning from below, dominant thinning led to only a modest increase in growth at intermediate basal areas (21–28 $m^2 \cdot ha^{-1}$) and stand ages less than 70 years. At high residual basal area (34 $m^2 \cdot ha^{-1}$), dominant thinning had no consistent effect on growth at any age, although it did decrease QMD relative to thinning from below.

Discussion

Our results extend the findings of Buckman et al. (2006) to additional growth measures by showing that dominant thinning generally resulted in greater basal area, volume, and biomass growth compared with thinning from below. These results contrast that of other studies that suggest stand-level volume and basal area growth tend to be similar regardless of thinning method (Spur et al. 1957, below vs. crown thinning; Cooley 1969, below vs. dominant vs. crown thinning; Seidel 1986, below vs. dominant thinning; Smith 2003, below vs. dominant vs. crown thinning; Gilmore et al. 2005, below vs. dominant thinning).

The dominant thinning method employed in our experiments was operationally, if not conceptually, a crown thinning. While the dominant and codominant trees with the largest diameter were removed preferentially (Buckman et al. 2006), the narrow range of diameters within the stand (ratio of mean diameter after to mean diameter before thinning was near 1.0) and the low percentage of trees in intermediate and suppressed crown classes (Buckman et al. 2006) essentially dictated that the thinning resulted in increased growing space for other dominant and codominant trees rather than a release of suppressed or intermediate crown classes, as would occur in a true dominant thinning. The exception to this may be the highest stocking treatment at Birch Lake (Fig. 1), where differentiation into crown classes likely did occur. As a result, the high thinning treatment at the highest stocking level was operationally a true dominant thinning that left less responsive residual trees, and consequently, the two thinning methods had virtually identical growth over time (Fig. 1). Oliver and Murray (1983) suggest that volume growth in Douglas-fir will be maximized in stand structures that have more large diameter trees in dominant and codominant crown classes, because intermediate and suppressed trees will not respond much or at all to increased growing space. Assuming red pine behaves similarly, the two thinning methods employed in our studies generally created stand structures that favored trees in dominant and codominant crown classes. The dominant thinning had the added benefit of increasing growing space to a greater degree around more of these individuals than did thinning from below, hence the greater gross growth with dominant thinning. It would be erroneous to conclude that growth would also be higher with a more typical dominant thinning, i.e., removing the largest stems in a stand preferentially, if the residual trees were largely in suppressed and intermediate crown classes.

Our results also illustrate that the relationship between thinning method and growth depends on stand age and stocking levels. Relative to thinning from below, dominant thinning had inconsistent impacts on increasing biomass, volume, and basal area growth within the range of conditions that are typical for commercially managed red pine stands, i.e., 21–28 $m^2 \cdot ha^{-1}$ basal area and <80 years old. The greatest differences in growth rates between thinning methods occurred at lower stocking levels (14–21 $m^2 \cdot ha^{-1}$) or in old stands (80–130 years old); conditions that are probably best managed for purposes other than maximizing wood yield, e.g., in the development of mixed species stands at low stocking levels or in the production of large saw or cabin logs on longer rotations.

Compared with thinning from below, dominant thinning resulted in less consistent and generally smaller increases in biomass growth than basal area growth. This difference was especially apparent in the Birch Lake study, where differences in biomass growth between dominant thinning and thinning from below were roughly half of the differences in basal area growth. This suggests that basal area may not be the best measure by which stand growth should be assessed if the goal is to identify approaches for increasing biomass yield for utilization in the emerging wood-based biofuels industry.

Thinning method did have a consistent and significant impact on mean tree diameters. QMDs were consistently lower with dominant thinning than with thinning from below, with the greatest differences occurring at the same basal areas and stand ages where the largest growth differences were realized. Despite higher stand-level growth with dominant thinning than with thinning from below, the economic value of dominant thinned stands for some products, such as cabin logs, poles, and saw timber, may actually be lower than that of stands thinned from below because of reduced mean diameters. Such differences in individual tree size and potential value should be considered as should stand level growth when making decisions about appropriate thinning method. In fact, the long biological life span of red pine (200+ years) and its ability to sustain diameter growth even at older ages (Rudolf 1990) make it an ideal species to grow in extended rotation situations, with the focus on individual tree growth.

Our results provide insight into the consequences of thinning strategies, using data from replicated long-term studies. The results illustrate that growth rates and yield in dominant thinned stands, relative to stands thinned from below, are dependent on both stocking level and stand age. Furthermore, our results suggest that growth rate trends are not consistent among basal area growth, volume growth, and biomass growth, and that the greater growth in dominant thinned stands than in stands thinned from below should be weighed against the effects of dominant thinning on individual tree size and potential value as poles and cabin logs.

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References

Bailey, J.D., and Tappeiner, J.C. 1998. Effects of thinning on structural development in 40- to 100-year-old Douglas-fir stands in western Oregon. For. Ecol. Manage. **108**(1–2): 99–113. doi:10.1016/S0378-1127(98)00216-3.

Buckman, R.E., Bishaw, B., Hanson, T.J., and Benford, F.A. 2006. Growth and yield of red pine in the Lake States. USDA For. Serv. Gen. Tech. Rep. NC-271. North Central Research Station, St. Paul, Minn., USA.

Cooley, J.H. 1969. Initial thinning in red pine plantations. USDA For. Serv. Res. Pap. NC-35. St. Paul, Minn., USA.

Curtis, R.O., and Marshall, D.D. 1988. Levels-of-growing-stock cooperative study in Douglas-fir. Report No. 8 — LOGS study: 20 year results. USDA For. Serv. Res. Pap. PNW-356.

Curtis, R.O., and Marshall, D.D. 2000. Why quadratic mean diameter? West. J. Appl. For. **15**: 137–139.

Drew, T.J., and Flewelling, J.W. 1979. Stand density management — an alternative approach and its application to Douglas-Fir plantations. For. Sci. **25**(3): 518–532.

Emmingham, W., Fletcher, R., Fitzgerald, S., and Bennett, M. 2007. Comparing tree and stand volume growth response to low and crown thinning in young natural Douglas-fir stands. West. J. Appl. For. **22**(2): 124–133.

Fowler, G.W. 1997. Individual tree volume equations for red pine in Michigan. North. J. Appl. For. **14**(2): 53–58.

Franklin, J.F., Spies, T., Perry, D., Harmon, M., and McKee, A. 1986. Modifying Douglas-fir management regimes for non-timber objectives. *In* Douglas-fir: stand management for the future. *Edited by* C.D. Oliver, D.P. Hanley, and J.A. Johnson. College of Forest Resources, University of Washington, Seattle, Wash., USA. pp. 373–379.

Franklin, J.F., Berg, D.R., Thornburgh, D.A., and Tappeiner, J.C. 1997. Alternative silvicultural approaches to timber harvesting: variable retention harvest systems. *In* Creating a forestry for the 21st century: the science of ecosystem management. *Edited by* K.K. Kolm and J.F. Franklin. Island Press, Washington, D.C., USA. pp. 111–139.

Gilmore, D.W., O'Brien, T.C., and Hoganson, H.M. 2005. Thinning red pine plantations and the Langsaeter hypothesis: a northern Minnesota case study. North. J. Appl. For. **22**(1): 19–26.

Hayes, J.P., Chan, S.S., Emmingham, W.H., Tappeiner, J.C., Kellogg, L.D., and Bailey, J.D. 1997. Wildlife response to thinning young forests in the Pacific Northwest. J. For. **95**(8): 28–33.

Helms, J.A. 1998. The dictionary of forestry. Society of American Foresters, Bethesda, Md., USA.

Husch, B., Beers, T.W., and Kershaw, J.A. 2003. Forest mensuration. John Wiley and Sons, Hoboken, N.J., USA.

Jenkins, J.C., Chojnacky, D.C., and Heath, L. S., and Birdsey, R.A. 2004. Comprehensive database of diameter-based biomass regressions for North American tree species. USDA For. Serv. Gen. Tech. Rep. RM-319.

Ker, M. 1980. Tree biomass equations for ten major species in Cumberland County, Nova Scotia. Inf. Rep. M-X-108. Canadian Forestry Service, Maritime Forest Research Center, Fredericton, N.S., Canada.

Miller, M., and Emmingham, W.H. 2001. Can selection thinning convert even-aged Douglas-fir stands to uneven-aged structures? West. J. Appl. For. **16**: 35–53.

Nyland, R.D. 1996. Silviculture concepts and applications. McGraw-Hill, New York, USA.

Oliver, C.D., and Murray, M.D. 1983. Stand structure, thinning prescriptions, and density indexes in a Douglas-Fir thinning study, western Washington, USA. Can. J. For. Res. **13**(1): 126–136. doi:10.1139/x83-019.

Rudolf, P.O. 1990. Red pine. Vol. 1. *In* Silvics of North America. *Edited by* R.M. Burns and B.H. Honkala. USDA For. Serv. Agric. Handb. No. 654. pp. 442–455.

SAS. 2001. System for Windows. Version 8.02 of the SAS System for Windows. SAS Institute Inc., Cary, N.C., USA.

Seidel, K.W. 1986. Growth and yield of western larch in response to several density levels and two thinning methods: 15-year results. USDA For. Serv. Res. Note PNW-RN-455.

Smith, D.W. 2003. Effects of thinning method on wood production in a red pine plantation. North. J. Appl. For. **20**: 39–42.

Smith, D.M., Larson, B.C., Kelty, M.J., and Ashton, P.M.S. 1997. The practice of silviculture: applied forest ecology. John Wiley and Sons, Inc., New York, USA.

Spur, S.H., Young, L.J., Barnes, B.V., and Hughes, E.L. 1957. Nine successive thinnings in a Michigan white pine plantation. J. For. **55**: 7–13.

Young, H.E., Ribe, J.H., and Wainwright, K. 1980. Weight tables for tree and shrub species in Maine. Misc. Rep. 230. University of Maine, Life Sciences and Agriculture Experiment Station, Orono, Maine, USA.