

## Research Article

# Leaf Area and Structural Changes after Thinning in Even-Aged *Picea rubens* and *Abies balsamea* Stands in Maine, USA

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We tested the hypothesis that changes in leaf area index ( $\text{LAI m}^2 \text{ m}^{-2}$ ) and mean stand diameter following thinning are due to thinning type and residual density. The ratios of pre- to postthinning diameter and LAI were used to assess structural changes between replicated crown, dominant, and low thinning treatments to 33% and 50% residual density in even-aged *Picea rubens* and *Abies balsamea* stands with and without a precommercial thinning history in Maine, USA. Diameter ratios varied predictably by thinning type: low thinnings were  $<0.7$ , crown thinnings were  $>0.7$  but  $<1.0$ , and dominant thinnings were  $>1.0$ . LAI change was affected by type and intensity of thinning. On average, 33% density reduction removed  $<50\%$  of LAI, whereas 50% density reduction removed  $>50\%$  of LAI. Overall reduction of LAI was generally greatest in dominant thinnings (54%), intermediate in crown thinnings (46%), and lowest in low thinnings (35%). Upon closer examination by crown classes, the postthinning distribution of LAI between upper and lower crown classes varied by thinning history, thinning method, and amount of density reduction.

## 1. Introduction

Leaf area index ( $\text{LAI m}^2 \text{ m}^{-2}$ ) is an important factor determining both tree and stand level production [1]. While LAI is biologically important due to the fact that foliage is where photosynthesis occurs [2], it is also arguably the most appropriate descriptor of growing space occupancy whether one is characterizing simple-structured, single-species forests [3, 4] or complex-structured, multispecies forests [5–7]. This importance is due to the strong well-established relationship between LAI and volume increment for both individual trees [8–11] and stands [12–14]. Accordingly, leaf area-based stocking models that incorporate these relationships have been developed as tools [6, 7, 15] giving managers the ability to base silvicultural retention on individual tree growth capability as opposed to simply diameter (DBH), although implementation is aided by taking advantage of the observed relationships between individual tree DBH and leaf area [9]. Given that LAI describes growing space occupancy and productivity, quantification of its relationship to silvicultural

activities, for example, intermediate thinning, should be of primary importance.

Thinning as a means to increase stand-level production, or more specifically the growth of some predetermined individuals, is an important part of silviculture [16]. Though we understand thinning does not increase overall growth *per se*, it can redirect the efficient use of growing space (i.e., LAI) to desired individuals [17, 18]. Traditionally, thinning is implemented in even-aged stands by reducing stand density through thoughtful removal of undesired individuals. Although the selection of trees for removal in thinning treatments can be characterized using the DBH distribution and DBH ratios [19, 20], actual implementation usually focuses on individual tree crown class, height, and position relative to neighbors. Because the amount of individual tree leaf area varies substantially, and predictably, between crown classes in even-aged stands [8, 9] and between cohorts in multiaged stands [3, 10, 13, 21], silviculturists are actually redistributing the LAI in a given stand. For example, when using thinning methods such as low thinning, crown

thinning, or selection thinning (henceforth called dominant thinning) removal is focused on trees from particular crown classes [19, 22]. Low thinning, or thinning from below, focuses removal on intermediate or suppressed trees with small crowns containing relatively little leaf area. Crown thinning, or thinning from above, focuses removal on codominant or dominant trees which have more leaf area than trees from the lower crown classes. Dominant thinning focuses removal on the largest crowned trees, which have substantial leaf area.

Given that thinning methods specify removing trees from different crown classes, we would expect the postthinning reduction in LAI to vary accordingly. The potentially large variation in postthinning LAI could have profound implications not only on subsequent stand volume increment [17], but also on ecological processes that have been linked to the redistribution of LAI through thinning [1]. For example, in a single-species stand, we might expect a low thinning to maintain a relatively large amount of LAI because primarily the intermediate and overtopped trees are removed [19]. In contrast, we might expect a crown or dominant thinning to have more drastic reductions in total LAI as a result of the removal of primarily dominant and codominant trees [19]. Holding thinning intensity constant, reoccupation of the growing space and higher postthinning volume growth would be achieved sooner after a low thinning than a crown or dominant thinning [17, 18, 23, 24] because primarily the upper crown classes are retained. Results of LAI changes due to thinning in mixed-species stands would likely vary proportionally with the species-specific [25, 26], and crown class differences in LAI, especially when species preference is part of the marking prescription. Previous work describing crown class changes as a result of intermediate thinning [27, 28] and natural stand development [29] provide a solid background for further understanding dynamics of LAI distribution between crown classes due to thinning methods.

In this study, we used a network of replicated commercial thinning treatments in Maine, the Cooperative Forestry Research Unit's Commercial Thinning Research Network (CTRN), to examine changes in structure and LAI after thinning activities in stands dominated by *Abies balsamea* (L.) Mill. and *Picea rubens* Sarg. [30]. Specifically, we question whether traditional commercial thinning methods that base selection for removal on crown classes result in predictable changes in postthinning structure and leaf area. We further question whether thinning type or intensity has an effect on the relationship between crown classes and leaf area.

## 2. Methods

Study sites, field methods, and leaf area sampling for this study were part of a larger research project on the production ecology of northeastern forests and were detailed in previously published papers [11, 31]. Methodological considerations specific to this study were reiterated for completeness.

**2.1. Study Sites.** The 12 CTRN sites span the Acadian forest region [32] in the state of Maine in the northeastern United States and are the result of even-aged regeneration methods

(often one-cut shelterwoods [19], still common in the region [30, 33]). Combinations of replicated low thinning, crown thinning, and dominant thinning treatments, to 33% and 50% relative density (RD) [34], were performed on the CTRN sites, which were divided evenly between a history of precommercial thinning (PCT), and no history of precommercial thinning (NOPCT) [30]. Six sites received PCT 15–20 years prior to the commercial thinning treatments (exact dates were undocumented), which occurred in 2000 and 2001. The PCT thinning focused on leaving evenly spaced trees regardless of diameter. The PCT sites were dominated by *A. balsamea*, ranged in age from 23 to 40 years and ranged in site index from 18.4 m to 24.3 m. The other six sites did not receive PCT (NOPCT) and were codominated by *P. rubens* and *A. balsamea*. The NOPCT sites ranged in age from 33 to 73 years and ranged in site index from 13.1 m to 21.5 m. Each thinning history (PCT versus NOPCT) independently consisted of a randomized-complete-block experimental design with replication of 6 plots per treatment. On the NOPCT sites, two intensities of thinning reduction (33% and 50% RD) and three commercial thinning methods (crown, dominant, and low) were performed. On the PCT sites, commercial thinnings to 33% and 50% of RD were performed on a time schedule. For this study, only one thinning entry had been conducted in the PCT ( $n = 6$  per thinning intensity, Table 1), so that the other plots were treated as controls ( $n = 30$ ). Each of the 12 CTRN sites had one designated control plot. Seven 0.02 ha measurement plots, nested within 0.08 ha treatment plots, were located at each site.

Prethinning data were used to calculate RD [34] for each site to guide marking. For the PCT sites, each of the seven plots within a site were ranked based on prethinning RD and assigned a commercial thinning treatment that did not result in stands of similar RD. Plots with median RDs were assigned as the control. Plots with first and the fifth highest ranking RDs were assigned to 33% RD and 50% RD reductions. Plots within the NOPCT sites were randomly assigned thinning treatments. Each plot was marked to the RD targets of 33% and 50%. Thinning goals were to remove all hardwoods, all *A. balsamea* greater than 21.6 cm DBH and to favor *P. rubens*. No consideration to RD reduction was given for harvester trails created during thinning operations. Common harvesting techniques included hand felling and four types of single-grip processors.

**2.2. Field Measurements.** Prior to thinning in each plot, every tree was measured for DBH and species was noted. In addition, crown class was noted for each tree, that is, codominant and dominant trees were considered upper crown classes, and intermediate and overtopped trees considered lower crown classes [19, 22].

Measurements taken after the thinning (~1–2 years later) had two goals, to characterize stand structure, and to predict individual tree leaf area from sapwood area. These data are referred to as stand structure data and sapwood area-leaf area data, respectively. Following harvest, every tree in each treatment unit (including control plots) was tagged with an individual tree number and measurements taken for DBH, height, height to the base of the live crown, crown class,

TABLE 1: Mean (standard deviation) and sample size by treatment type and thinning history for pre- and postthinning leaf area index (LAI) and relative density<sup>a</sup> (RD).

| Thinning treatment | Prethinning<br>LAI (m <sup>2</sup> m <sup>-2</sup> ) | RD          | Postthinning<br>LAI (m <sup>2</sup> m <sup>-2</sup> ) | RD          | Number of plots |
|--------------------|------------------------------------------------------|-------------|-------------------------------------------------------|-------------|-----------------|
| NOPCT              |                                                      |             |                                                       |             |                 |
| Crown 33%          | 10.7 (2.3)                                           | 0.59 (0.06) | 6.4 (1.9)                                             | 0.35 (0.02) | 6               |
| Crown 50%          | 10.9 (2.8)                                           | 0.61 (0.09) | 5.1 (1.2)                                             | 0.28 (0.02) | 6               |
| Dominant 33%       | 10.7 (1.8)                                           | 0.59 (0.05) | 5.9 (1.9)                                             | 0.34 (0.06) | 6               |
| Dominant 50%       | 11.0 (3.3)                                           | 0.58 (0.09) | 4.2 (1.4)                                             | 0.26 (0.05) | 6               |
| Low 33%            | 9.8 (1.7)                                            | 0.59 (0.09) | 7.2 (1.9)                                             | 0.36 (0.05) | 6               |
| Low 50%            | 10.2 (2.2)                                           | 0.59 (0.04) | 5.8 (1.7)                                             | 0.28 (0.05) | 6               |
| Control            | 9.7 (1.7)                                            | 0.60 (0.09) | 10.9 (2.1)                                            | 0.69 (0.12) | 6               |
| PCT                |                                                      |             |                                                       |             |                 |
| 33% Reduction      | 12.2 (0.9)                                           | 0.36 (0.03) | 7.8 (0.7)                                             | 0.24 (0.02) | 6               |
| 50% Reduction      | 10.1 (1.3)                                           | 0.31 (0.05) | 4.9 (0.6)                                             | 0.15 (0.02) | 6               |
| Control            | 10.4 (1.7)                                           | 0.31 (0.05) | 11.6 (1.9)                                            | 0.36 (0.05) | 30              |

<sup>a</sup> Relative density calculated according to Wilson et al. [34]. Note: PCT—precommercial thinning history, NOPCT—no history of precommercial thinning.

and species. A systematic sample was developed from the postthinning tally of tagged trees by arraying them as three live crown ratio classes (crown length/height) by 5.1 cm DBH classes. From each cell in this matrix, every tenth tree was selected for sampling. For each of these trees, measurements included DBH; bark thickness, measured at breast height on the north and east sides of the tree; height; height to the lowest live branch. Crown class designations were given to each tree [19, 22, 35]. Two increment cores per tree were taken 90° apart at breast height using a cordless power drill and increment borer [36]. The sapwood boundary was delineated immediately in the field by holding each core to light and marking the boundary between the translucent sapwood and opaque heartwood. Cores were glued into routed boards where both bark and sapwood boundaries were marked with an indelible pencil for subsequent laboratory analysis. Trees were measured one or two growing seasons after thinning, prior to detectable DBH or leaf area growth responses. Sampling for sapwood area-leaf area was conducted in the dominant thinning, low thinning, and control plots at each installation of the NOPCT history. For the PCT sites, two treated plots (33% and 50% reduction) and two untreated plots with the greatest RD were measured.

**2.3. Leaf Area Sampling.** Relationships for indirectly estimating individual tree leaf area were developed by destructively sampling seven or eight trees per site during summer 2001. A total of 88 trees covering a range of DBHs and crown classes were chosen from plot buffers at each of the 12 sites. *A. balsamea* was sampled from PCT plots, while *P. rubens* was sampled from NOPCT plots. After felling, total tree height and height to base of the live crown were measured directly. Sample branches were taken from three random locations within the crown to build predictive models of branch leaf area. The sampling locations were one from the upper half of the crown; one each from the two lower quartiles, divided this way to account for foliage recession on older branches and for potential differences in specific leaf area with crown depth [37–39]. Branch basal diameters and branch length

were measured. Approximately 100 needles were removed from across the range of needle ages for each branch for subsequent analysis.

**2.4. Sapwood Area Measurement.** Increment cores were measured for tree-ring increment (0.001 mm) and to determine the radial length of sapwood. Before making any calculations, ring widths were adjusted for shrinkage using the following factors: *A. balsamea*, 2.9%; *P. rubens*, 3.8% [40]. Estimates of sapwood area were then determined for each tree by subtracting the north and east core sapwood radii from the inside bark diameter, then these estimates of heartwood area were averaged before subtracting from the averaged inside bark basal areas. Final estimates of sapwood area were used in combination with other tree metrics for the prediction of leaf area.

**2.5. Branch and Tree Leaf Area Prediction.** Projected needle areas were measured using WinSeedle scanning software (Regent Instruments). Needle area measurements were combined with needle weights (g) to determine specific leaf area for each randomly sampled branch. Specific leaf area was then multiplied by the weight of all needles to determine branch leaf area. Branch-level equations from [11] were applied to every branch in each tree crown before summing for individual tree leaf area.

For *A. balsamea*,

$$\sqrt{(\text{BRLA})} = 129.79 * \text{BRD}^{1.049} * \text{RDINC}^{(1.923-1)} \exp [-(1.959 * \text{RDINC}^{1.923})], R^2 = 0.91,$$

for *P. rubens* codominant, dominant, and intermediate trees,

$$\ln \text{BRLA} = 8.375 + 2.084 * \ln \text{BRD} + 0.705 * \ln \text{RDINC} - 2.652 * \text{RDINC}, R^2 = 0.83, \log \text{bias ratio correction factor} = 1.1657 [41], \text{ and}$$

for *P. rubens* overtopped trees,

$$\ln \text{BRLA} = 2.754 + 2.872 * \text{BRD}, R^2 = 0.79, \log \text{bias ratio correction factor} = 1.1826,$$

where BRLA is predicted branch leaf area ( $\text{cm}^2$ ); BRD is branch basal diameter (mm); RDINC is relative depth into the crown, measured from the leader to the lowest live branch.

Equations for predicting individual tree leaf area (PLA) from sapwood area and crown length reported in [11, 31] were applied to the sapwood area-leaf area data in this study. For *A. balsamea*,

$$\ln \text{PLA} = -1.692 + 0.863 * \ln \text{SA} + 0.797 * \ln \text{CL}, R^2 = 0.96, n = 43, \text{ log bias ratio correction factor} = 1.0322,$$

for *P. rubens*,

$$\ln \text{PLA} = -2.722 + 0.966 * \ln \text{SA} + 0.844 * \ln \text{CL}, R^2 = 0.91, n = 45, \text{ log bias ratio correction factor} = 0.9753,$$

where PLA is projected individual tree leaf area in  $\text{m}^2$  per  $\text{m}^{-2}$  of ground area, SA is sapwood area ( $\text{cm}^2$ ), and CL is crown length (m).

The sapwood area equations were then used to estimate PLA for every tree measured in the stand structure data. From these results, site-specific [42] PLA models were developed using stepwise regression techniques for the purpose of predicting leaf area of noncored trees. Combinations of the model form  $\ln \text{PLA} = b_0 + b_1 \ln \text{DBH} + b_2 \ln \text{DBH}^2 + \text{SITE} + \varepsilon$  were used where the SITE is a site-specific parameter and  $\varepsilon$  represents random error. Where application of a site-specific model was not possible, due to limited representation of a species, a model fit from the destructively sampled trees (which span all sites) was used. Resultant models performed well (84%–95% variation accounted for), and residual analysis for each model ensured unbiased predictions across independent variables and validated linear model assumptions.

**2.6. LAI Estimation.** PLA for individual trees on each plot were converted to all-sided leaf areas using published ratios of 2.3 for *A. balsamea* [43] and 2.9 for *P. rubens* [44] in order to take into account differences in needle morphology between species [2]. All-sided leaf area likely better integrates physiological processes such as light interception and respiration because it takes into account the entire photosynthesizing surface of needles in comparison to the more common one-sided PLA. More importantly, standardizing leaf area estimates between *A. balsamea* and *P. rubens* before combining into plot level LAI should reduce or eliminate any species-specific affect on LAI. LAI was calculated by summing individual tree all-sided leaf area for all *A. balsamea* and *P. rubens* on each plot during the prethinning analysis, and again for the postthinning stand structure data (Table 1). LAI estimates reported henceforth in this study are all-sided leaf areas. The change in LAI for each plot was calculated by dividing the post-thinning LAI by the prethinning LAI and subtracting 1.0 to reflect the decrease in LAI that occurred in all plots except the untreated controls.

**2.7. Analysis.** Given the differences in study design and implementation, no statistical tests between attributes associated with PCT and NOPCT histories were made. To assess

the effect of thinning method on stand structure, a ratio ( $d/D$ ) of mean plot DBH before thinning to mean plot DBH after treatment was calculated and analyzed between treatments using one-way ANOVAs. This ratio is similar to the “ $d/D$ ” ratio mentioned in [19] and was used for yield projections in relation to thinning methods [45]; however, DBH of trees removed during thinning was not measured in this study, instead mean posttreatment DBH was used. To assess the effect of thinning method and species composition change (Table 1) on LAI, the proportional change in LAI from pre- to postthinning for each treatment was analyzed using one-way ANOVAs. Potential LAI differences associated with species composition effects were assessed by including a variable which described the net change in percent *P. rubens* for each plot from pre- to postthinning for the NOPCT histories (range  $-0.02\%$ – $0.05\%$ ). PCT stands were not tested for species composition effects because the net change in composition pre- to postthinning was  $<1\%$ . Preliminary results suggested the percent *P. rubens* effect ( $P = 0.556$ ) and the percent *P. rubens* by treatment effect ( $P = 0.338$ ) were insignificant; therefore, subsequent analyses were interpreted solely as treatment effects. We also examined the possible postthinning shift in the distribution of LAI between crown classes within thinning types. This was done by calculating the postthinning proportional change in LAI by upper and lower crown classes relative to the prethinning LAI and plotting them for all but the crown thinning treatment. Due to time constraints, canopy information was not collected for the crown thinning treatment during posttreatment measurements, so they were not included in this analysis. As a result of limited pretreatment measurements, posttreatment crown classes were grouped into upper (dominant and codominant trees) and lower (overtopped and intermediate trees) crown classes in order to investigate the shift in LAI by treatment. We confirmed that independence, normality, and constancy of error variance assumptions for ANOVA were met. Pair-wise means tests were performed using Tukey’s test. All statistical tests were considered significant at the  $P < 0.05$  level.

### 3. Results

**3.1. NOPCT.** The  $d/D$  ratio was  $<1.0$  in the NOPCT low thinning treatment plots, which indicated that indeed smaller DBH trees were removed during the thinning. Similarly, the dominant thinning in the NOPCT resulted in  $d/D > 1.0$ , but only for the 50% reduction. The 33% reduction had mixed results and was not significantly different from 1.0. Both crown thinning reduction levels had  $d/D$ s well below 1.0, which indicated that, although dominant and codominant trees may have been selected during thinning, proportionally more small DBH trees were removed (Figure 1). NOPCT control plots had  $d/D$ s  $< 1.0$  which indicated diameter increment between measurement periods ( $\sim 1$  to 2 years).

Although strictly marked to postthinning relative densities, the LAI reductions for NOPCT plots were proportional to thinning intensity (33% or 50%) and to a lesser extent thinning type (low, crown, or dominant). For NOPCT

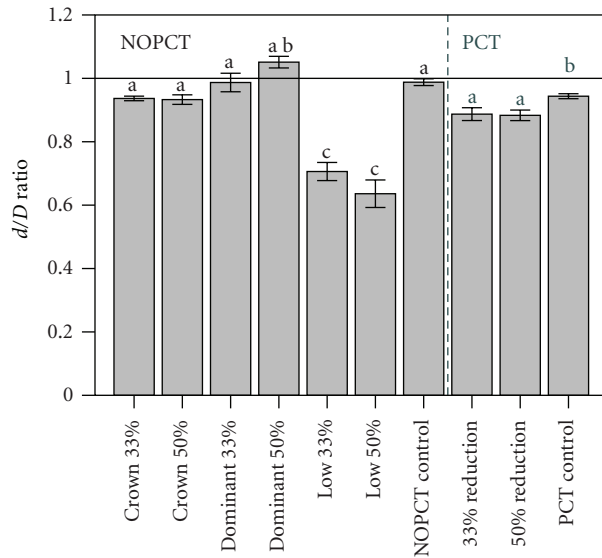


FIGURE 1: Mean  $\pm$  one standard error pre- to postthinning average diameter ratios ( $d/D$ ) for the commercial thinning types (crown, dominant, low) and reduction levels (33% and 50%) implemented by the Cooperative Forestry Research Unit Commercial Thinning Research Network. Statistical analysis was conducted independently for PCT (precommercial thinning history) and NOPCT (no history of precommercial thinning) groups. Letters represent significant differences determined using Tukey's test.

thinning types, absolute LAI reduction averaged 35% for low thinning, 46% for crown thinning, and 54% for dominant thinning (Figure 2). Similarly, for each thinning type, the difference in the reduction of LAI between the 33% and 50% RD treatments averaged 13% for crown thinning, 16% for dominant thinning, and 14% for low thinning (Figure 2). The NOPCT control plots increased LAI by  $\sim 12\%$  due to growth between measurement periods.

The reduction in LAI due to thinning type resulted from drastically different postthinning distributions of LAI between crown classes. The NOPCT low thinning 33% reduction treatment resulted in 10% more leaf area in the upper crown classes and 60% less in the lower crown classes relative to prethinning (Figure 3). Here, trees marked for removal were generally smaller in DBH and from the lower crown classes, and resulted in a 27% reduction in LAI for a 33% reduction in RD. Dominant thinning to 50% resulted in relatively more postthinning LAI in the lower crown classes and relatively less postthinning LAI in the upper canopy classes, as was expected when removing primarily dominants (large DBH), and which resulted in a 62% reduction in LAI for a 50% reduction in RD. In contrast, dominant thinning to 33% resulted in a 55% decrease in LAI for a 33% reduction in RD, even though the relative amount of postthinning LAI in the upper crown classes increased (Figure 3). NOPCT controls had a net negative change in LAI in the lower crown classes and only a small positive LAI change in the upper crown classes, which likely indicated plots were undergoing strong size class differentiation. With the possible exception of low thinning, patterns of postthinning LAI redistribution

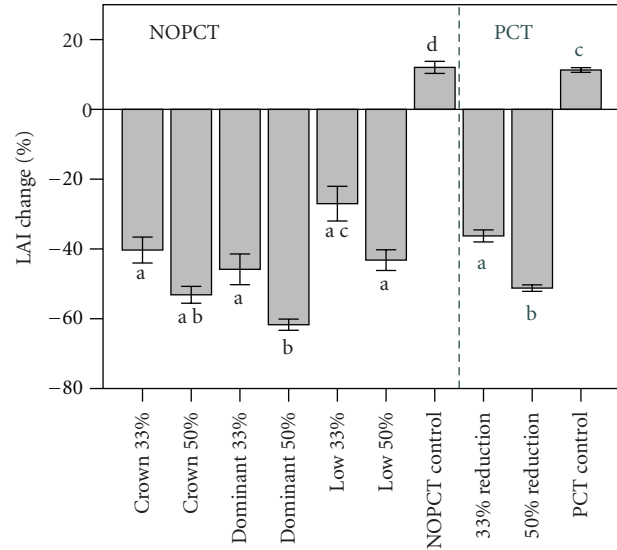


FIGURE 2: Direction and magnitude of net leaf area index (LAI) changes for the commercial thinning types (crown, dominant, low) and reduction levels (33% and 50%) implemented by the Cooperative Forestry Research Unit Commercial Thinning Research Network. Statistical analysis was conducted independently for PCT (precommercial thinning history) and NOPCT (no history of precommercial thinning) groups. Letters represent significant differences determined using Tukey's test.

by crown class were not readily predictable by thinning type or intensity.

**3.2. PCT.** The  $d/D$  ratio was  $<1.0$  for PCT plots with 33% and 50% RD reductions, which indicated primarily smaller DBH trees were removed during thinning (Figure 1). The  $d/D$  ratio was also  $<1.0$  for PCT control plots, the result of diameter growth between measurement periods.

LAI change in the PCT plots was more severe with a 50% RD reduction relative to the 33% RD reduction. Absolute LAI reduction in PCT plots averaged 36% for the 33% RD reduction and 51% for the 50% RD reduction (Figure 2). In addition, the difference in total LAI reduction between the 33% and 50% RD treatments was only 8% on average (Figure 2). Like the NOPCT controls, the PCT control plots increased in LAI between measurement periods by  $\sim 11\%$  as a result of growth between measurement periods.

Changes in PCT plot LAIs due to RD reduction resulted from strikingly different postthinning distributions of LAI between crown classes. While the 50% RD treatment resulted in a 49% reduction in total LAI and a net increase in lower crown class LAI (Figure 3), the 33% RD treatment resulted in a 36% reduction in total LAI through a net decrease in lower crown class LAI (Figure 3). In contrast to the NOPCT controls, PCT control plots had an unexpected net positive change in lower crown class LAI, suggesting an influence of PCT stand history on subsequent stand dynamics. Similar to the NOPCT results, patterns of postthinning LAI between crown classes were not predictable from RD treatments.

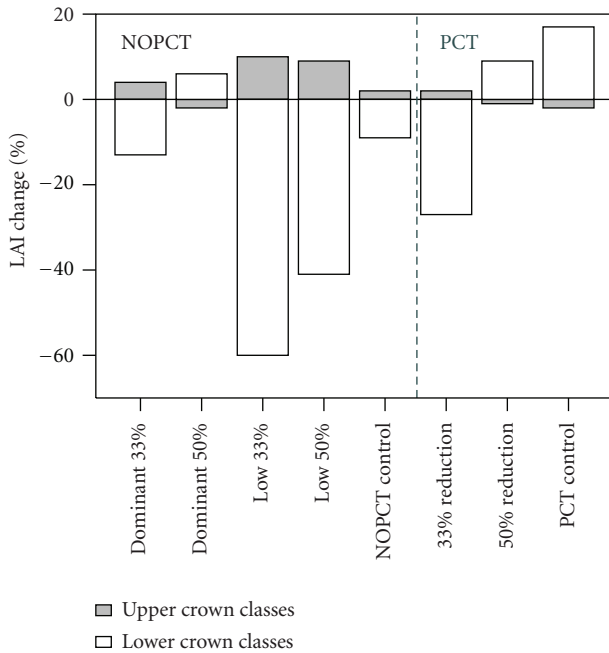


FIGURE 3: Direction and magnitude of leaf area change by crown classes (upper and lower) for the commercial thinning types (dominant, low) and reduction levels (33% and 50%) implemented by the Cooperative Forestry Research Unit Commercial Thinning Research Network. Note. PCT—precommercial thinning history, NOPCT—no history of precommercial thinning. Crown thinning canopy level information was not collected.

#### 4. Discussion

Based on the thinning types, one would expect low thinning to have a  $d/D$  of  $<1.0$ , dominant thinning  $>1.0$  and crown thinning approximately equal to  $1.0$ . These expectations are similar to the guidelines proposed by Vezina [46] (low thinning  $<0.7$ , crown thinning  $0.7$  to  $1.0$  and dominant  $>1.0$ ). However, the relationships for dominant and crown thinning in our data are more vague, likely a result of two factors: (1) the use of posttreatment DBH in our calculations of  $d/D$  that are not directly comparable with the guidelines suggested by Vezina [46]; (2) strict adherence to percent RD reductions (33% and 50%) during marking the CTRN. For example, in one case codominant and dominant trees were iteratively marked and remarked until the RD target for crown thinning was met. That the dominant 50% treatment has a higher  $d/D$  in every case suggests larger trees had to be removed to meet the RD target, which has a measurable effect on the shift in proportion of LAI between upper and lower crown classes postthinning (Figure 3). Although the NOPCT low thinning treatment  $d/D$ s are substantially lower than  $1.0$ , both PCT RD reductions (33% and 50%) also averaged just under  $1.0$  ( $\sim 0.89$ ), resulting in stand structure that suggests lower crown classes were more likely marked for thinning.

While overall LAI reduction was predictable from stand history (NOPCT versus PCT), RD reduction, and thinning type, differences in the postthinning LAI distribution between crown classes requires further scrutiny. For example,

the PCT 50% RD reduction and the dominant thinning 50% RD reduction both show a shift in the distribution of LAI from the upper to the lower crown classes. We suggest the similarity in crown class results for these two treatments stems from the need to mark enough trees for removal to meet the RD target, resulting in some relatively large-crowned trees being removed. In addition, the  $d/D$  for the dominant thinning to 50% RD suggests that more large DBH trees (upper crown classes) were removed. This explains why there is a relative reduction of LAI from the upper crown classes. Whereas the  $d/D$  for dominant thinning to 33% RD suggests trees were removed uniformly from the DBH distribution, as opposed to large DBH trees as prescribed, so that the postthinning distribution of LAI between crown classes is similar to the NOPCT control (Figure 3) [27].

Another possible reason postthinning crown class LAI distribution was variable might be the differences in stand history (i.e., NOPCT and PCT). The similarity in  $d/D$  between the NOPCT and PCT controls does not explain their postthinning difference in LAI. In the PCT control plots, the proportion of postthinning LAI in the lower crown classes increased, whereas the proportion of LAI in upper crown classes increased on the NOPCT control plots (Figure 3). One possible explanation is that the older NOPCT plots are undergoing strong self-thinning so mortality of intermediate and overtopped trees is likely due to competition related, density-dependent mortality [47] which has been found to maintain dominant and codominant trees [27, 29]. Conversely, the younger PCT plots have wider spacing than NOPCT plots and homogenized diameters a result of the PCT. This likely explains why the  $d/D$ s are not substantially lower than  $1.0$ . While the PCT plots are likely undergoing differentiation into size classes [28] because of widening crowns [48], they are probably not self-thinning because of the precommercial thinning, so that any intermediate and overtopped trees that were not cut have persisted and subsequently enlarged their crowns. Furthermore, when conducting a precommercial thinning, multiple criteria are taken into consideration [49, 50]. Typically, workers simultaneously consider intertree spacing, species preference, and size. The PCT treatment history in this study area prioritized size and spacing, but not species. As a result, primarily the largest diameter *A. balsamea*, which tend to grow more rapidly than *P. rubens* early in stand development [51], were retained during thinning and smaller individuals were removed, which would further narrow the size distribution. Another possible explanation is that the subjectivity of crown class determination [35] is exacerbated when plots that have been precommercially thinned are scrutinized during field measurements.

Differences in the distribution of LAI between the upper and lower crown classes could have implications for the ability of the postthinning stands to reoccupy the growing space. In general, posttreatment LAI in the PCT plots should reoccupy the growing space faster than the NOPCT plots due to their higher potential productivity [11, 52], which is in part a result of the fact that higher quality sites are typically chosen to receive PCT [49]. However, in order to positively affect the potential increase of individual tree

LA and growth typically sought by reducing stand density [53], careful attention must be paid to whether the type of thinning employed removes trees from the appropriate crown classes. For example, the PCT 33% RD reduction resulted in a net loss of LAI from the lower crown classes and a net gain in LAI from the upper crown classes. In general, these dominant and codominant trees have more individual tree leaf area [8, 9], and their higher growth potential ought to translate into an increase in postthinning individual tree growth increment, compared to trees of similar size on control plots [54]. Juodvalkis et al. [48] note that the effect of thinning on individual tree growth (DBH and crown reaction) is most pronounced when thinning occurs early in stand age, as was the case for the CTRN precommercial thinning. However, as a result of this historic spacing in the PCT stands, higher individual tree growth [55] might come at the expense of stand volume growth if the trees do not fully reoccupy the growing space, which may be especially problematic in the 50% RD reduction treatments.

Because stand volume production is strongly linked to LAI [13, 14], and thinning has been demonstrated to result in subsequent rapid LAI increase relative to controls [56], it is realistic to expect changes in volume increment proportional to the quantity of LAI as a result of thinning type and intensity [57]. A thorough review of long-term stand volume response to thinning to various intensities reveals mixed results regarding comparisons between thinning intensities, thinning types, and their controls over fixed time periods [58]. Furthermore, while a lengthy literature discusses potential stand volume changes due to thinning [17], there is likely a point beyond which thinning intensity reduces potential subsequent stand yield. This idea of an optimum stand density for growth is not new [17, 24, 59] but the empirical evidence is mixed. For example, long-term increases in stand volume production were correlated with thinning intensity, where maximum volume increment for *P. abies* was ~15% greater than controls for 30-to-40-year-old stands, and the volume increase was most pronounced for the youngest thinned stands [48]. In another example, low thinning was found to result in the highest long-term production of *P. abies*, followed by crown thinning, and dominant thinning [60]. In contrast, mid-term (15 year) stand volume of all thinning intensities were found to be lower than controls in mixed stands of *P. abies*-*Betula pubescens* Erhr [61]. Similarly, Slodicak et al. [62] noted long-term (29 years) stand volume reductions ranging from 14 to 23%, with larger reductions in crown thinning, which they attributed to site or “other” conditions. Based on our results, it is possible those “other” conditions might be explained as the size (i.e., DBH) of trees that were selected for removal.

One possible limitation of our study is the prediction of leaf area in mixed species stands. For example, although stands of *Pinus contorta* var. *latifolia* (Engelm.) Critchfield and *Abies lasiocarpa* (Hook.) Nutt have relatively similar stand growth efficiencies (stemwood increment per unit leaf area) [25], this was likely the result of the relatively efficient individual tree use of lower absolute LAI in *P. contorta* than in *A. lasiocarpa*, and this was likely mediated by stand structure [63]. Conversely, both LAI and growth efficiency

differ greatly in stands of mixed *Picea abies* (L.) Karst-*Pinus sylvestris* L. in Finland where the difference was related to species composition [26]. In this study, we account for the potential differences in leaf area between *A. balsamea* and *P. rubens*, which are both shade tolerant and had very similar individual tree leaf areas to begin with [9, 10], in two ways: (1) we used all-sided leaf area conversion factors before estimating LAI in our methodology; (2) we subsequently conducted a preliminary analysis for species effect using net change in percent *P. rubens* as a measure of composition change from pre- to postthinning for the NOPCT data, which had nonsignificant results. All-sided conversions minimize potential differences in absolute LAIs due to species, which likely explains the insignificance of net change in percent *P. rubens* composition when included in the analysis. In addition, although it is possible to have similar LAIs at drastically different structures, all CTRN stands are even-aged with strong unimodal DBH distributions, so that DBH distributions probably do not explain LAI differences *sensu* O'Hara [12]. Therefore, our results and interpretation reflect the influence of treatment type and RD reduction on LAI changes and not species-specific effects.

## 5. Management Considerations

Although not necessarily desirable in practice, the relatively severe reductions of LAI imposed as part of the CTRN provide useful benchmarks for future work. In the CTRN study, strict adherence to marking guidelines ensured that contrasts between treatments were enhanced [30]; however, relaxing these assumptions in practice might have a less drastic effect on LAI and its potentially unintended redistribution between crown classes. Of course, the practical trade-off for low thinning is the need to remove a larger number of small DBH stems in order to meet the RD target. This is often not practical from an economical harvesting perspective without removing some larger DBH stems. In contrast, when marking a dominant thinning perhaps the most difficult procedure is balancing the removal of poorly formed dominants with the desired residual density while not succumbing to high grading [19]. Stands with a history of PCT, on the other hand, will have more merchantable stems earlier in the rotation [64], potentially making removal of the smaller portion of stems financially feasible.

Based on our results, commercial thinning tends to redistribute LAI predictably; however, there is some variability in the observed relationships. This suggests that, although a particular type of thinning is prescribed (e.g., dominant thinning), actual RD reduction will not necessarily meet the goals associated with the treatment. In a region where arguably little silviculture is conducted, silviculturists designing marking guidelines for even-aged *P. rubens*-*A. balsamea* forests might consider relaxing strict adherence to density reduction targets, which may result in unanticipated shifts in LAI from one crown class to another and result in unanticipated effects on subsequent growth. Instead, we recommend focusing on leaving trees of appropriate species and growth capability (i.e., *P. rubens*, or small-crowned

codominants) so that growing stock is not overly reduced and growing space can be rapidly reoccupied after treatment.

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