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Article

Integrating silviculture with hemlock woolly adelgid mitigation: crown dynamics of *Tsuga canadensis* (L.) Carrière 10 years after thinning

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Abstract

Pre-emptive silvicultural treatments can enhance host-tree vigor as a component of an integrated management approach to mitigate invasive species' impacts. Hemlock woolly adelgid (HWA, *Adelges tsugae* Annand, 1928) threatens the health and existence of eastern hemlock-dominated forests. We propose that increasing canopy light exposure via silvicultural thinning can reduce hemlock's vulnerability to HWA. Three stands with high hemlock densities on the Allegheny National Forest were selected for thinning. There was no HWA infestation and half of each stand was thinned. Circular plots were established surrounding 96 hemlock "subject trees" targeted for crown release on 3–4 sides. Similar criteria were used to select 90 hemlocks in untreated plots. We visited subject trees pre-thinning and 5 and 10 years post thinning and measured the following: diameter, total height, live crown ratio, and crown area. Temporal changes in diameter were not significant between treatments, but trees in thinned plots averaged 5 cm larger after 10 years. Live crown ratio was maintained in thinned stands and decreased after year 5 in controls. Crown area increased in thinned plots and decreased in controls. Residual basal area significantly influenced growth but varied between treatments and among stands.

Key words: eastern hemlock silviculture, *Tsuga canadensis*, hemlock woolly adelgid, thinning

Introduction

Since the 1950s, hemlock woolly adelgid (HWA) has been a major threat to forest ecosystem health and economic viability of eastern North American hemlock species—eastern hemlock *Tsuga canadensis* (L.) Carrière and Carolina hemlock *T. caroliniana* Engelm. (Knauer et al. 2002). Eastern hemlock *Tsuga canadensis* (L.) Carrière is distributed from the southern Appalachian Mountains to southeastern Canada and westward to the central Lake States (McWilliams and Schmidt 2000). It is a long-lived, shade-tolerant conifer occurring in pure and mixed stands across a range of primarily mesic sites (Godman and Lancaster 1990). Because hemlock stands contribute unique structural and functional landscape attributes, hemlock is considered a foundation species with a specific role in ecosystem processes (Ellison et al. 2005). Hemlock's shade tolerance and slow growth habit result in dense, multi-layered canopies (Fajvan and Seymour 1993) important to terrestrial and aquatic wildlife habitat (Snyder et al. 2002; Tingley et al. 2002).

Since its introduction, HWA has spread (Evans and Gregoire 2007; Morin et al. 2009) and infested hemlock throughout most of its range (USDA Forest Service 2019). Wide-ranging hemlock decline/mortality rates suggest that tree health, stand structure, and site variables influence hemlock's vulnerability to HWA feeding (Pontius et al. 2002; Rentch et al. 2009). Hemlocks in dominant and codominant overstory crown-class positions appear to survive HWA longer than intermediate and overtopped crown-class trees (Orwig and Foster 1998; Eschtruth et al. 2006). Tree-crown variables are also more likely to reliably predict the degree of hemlock decline after infestation. The effects of HWA on the rate of hemlock-growth decline and mortality have been correlated with crown class and live-crown ratio (LCR) (Rentch et al. 2009). LCR is the ratio of crown length (an estimate of the potential photosynthetic surface area) to tree height (an estimate of the total respiration area) (Oliver and Larson 1996). Anecdotally, infested hemlock crowns receiving full sunlight, such as those growing along forest edges or in gaps, appear to survive longer than trees growing in shade. Higher light and temperature (Brantley et al. 2017; Lapham et al. 2018) may negatively affect HWA survival and promote new shoot growth (Ford Miniat et al. 2020). In the field, changes in hemlock radial growth have been correlated with degree of HWA infestation and crown size attributes (Rentch et al. 2009). Under controlled ambient light environments, HWA densities on hemlock seedlings decreased with increasing light as leaf and root starch content, and growth, continued to increase (Brantly et al. 2017).

Reductions in stand densities via silvicultural manipulations alter forest climate and soil and foliar nutrient cycles (Van Cleve and Zasada 1976). Thinnings reallocate fixed resources among fewer stems, which increases the amount of light, water, and nutrients per tree and enhances growth. A tree's foliar canopy can be considered a carbohydrate source and all other living tissues as a sink; hence, there is a relationship to tree survival and growth based on the relative sizes of the source and sink (Oliver and Larson 1996). Foliar quantity is affected because of modifications to branch size–foliage weight relationship and the number and(or) size of branches within the crown (Gillespie et al. 1994). Increasing crown size could improve a tree's ability to deal with stressors, including insect attack (Waring and Pitman 1985; Knauer et al. 2002; Fajvan et al. 2008).

Scientific and anecdotal evidence suggests that while healthy hemlocks are not less susceptible to HWA attack, they do have a better chance of surviving longer than trees stressed by crowded conditions and shading (McClure 1995; Sivaramakrishnan and Berlyn 2000), possibly due to environmental conditions less suitable for HWA survival (Brantley et al. 2017). Maintenance of healthy trees through thinning has been proposed as part of an integrated strategy combined with chemical and biological HWA controls (Mayfield et al. 2015).

The effectiveness of silvicultural treatments for improving resource acquisition and hemlock health in mixed-species stands has not been extensively studied. There are few thinning studies in mixed-species stands containing a significant hemlock component (>30% basal area) that focus on reducing stand density specifically to favor hemlock growth (Fajvan 2008). Hemlock height and diameter growth after crown release are related to preharvest stand density and canopy status (overstory vs. understory) (Merrill and Hawley 1924; Marshall 1927). Trees growing in dense stands showed 60% greater height and diameter growth after thinning (from above and below) than stands that were understocked. Age appears to be a minor factor in hemlock growth response; older trees typically grow better than younger ones unless prolonged suppression (>60 years) has significantly reduced crown area (Marshall 1927; Fajvan and Seymour 1993).

We initiated a study in 2005 to determine whether stand structure manipulations can be used ahead of the leading edge of HWA invasion to improve individual host-tree health and growth by reducing crown shading. Specifically, we designed thinnings to reduce relative stand densities in hemlock-hardwood stands to reallocate site resources and enhance the health of the remaining hemlocks (Fajvan 2008). Our original study objective was to determine whether thinning hemlock-hardwood stands would improve or maintain hemlock health and crown attributes by influencing LCR and crown area (CRAREA) prior to HWA arrival. Three PA stands on the Allegheny National Forest (ANF) were thinned in 2007 and have been monitored for 10 years. However, there has been no infestation to date even though HWA is established in numerous sites across the forest. In this paper, we present the findings from intensive monitoring of 186 "subject" trees, where approximately half received direct crown release on 3–4 sides in thinned plots. We compare the changes in growth parameters between trees with released crowns and those without release to assess the efficacy of the treatment on hemlock health but cannot make inferences regarding HWA susceptibility at this time.

Methods

Study area and treatment

Three 24–32 ha stands were selected on the ANF in northwestern PA, USA, near the town of Warren, 41.64976°N, 79.03913°W. The forest covers about 210 000 ha and is 90% forested with an average elevation of 427 m. Vegetation consists of second-growth, 70–100-year-old mixed Allegheny hardwood species, dominated by black cherry (*Prunus serotina* Ehrh.), red maple (*Acer rubrum* L.), black birch (*Betula lenta* L.), yellow birch (*Betula alleghaniensis* Britton), northern red oak (*Quercus rubra* L.), sugar maple (*Acer saccharum* Marshall), and American beech (*Fagus grandifolia* Ehrh.). Hemlock is found either in pure patches or dispersed within the hardwoods, which comprise 89.2% of inventoried basal area (trees > 12.7 cm); hemlock basal area comprises 9.8%. The ANF has a moderate climate, with warm and humid summers. Average temperatures range from 23.9 to 26.7 °C (75–80 °F) in summer to −3.9 to −6.7 °C (20–25 °F) in winter, and mean annual precipitation ranges from 889 to 1295 mm. (USDA Forest Service 2018).

The study stands are located on the ANF Bradford Ranger District in compartment 301. This compartment was selected because of the unusually high proportion of hemlock (24%–38% of study area basal area) and very high total relative stand densities, which affect net growth due to crowded conditions. High hemlock abundance was the main contributor to these conditions. Soils in the project area belong to two main soil groups—Cavode silt loams with 0%–8% slope, classified as poorly drained, and Cookport very stony silt loams, with 0%–15% slope, considered moderately well drained.

Stand selection was determined based on feasibility of conducting a commercial harvest: minimum size 24 ha and minimum hemlock basal area of 7 $m^2 \cdot ha^{-1}$. The selected stands had total basal areas ranging from 42 to 48 $m^2 \cdot ha^{-1}$. These stands were further distinguished based on the overstory dominance of either black cherry or red oak and red maple. Hemlock content ranged from 11.5 to 16 $m^2 \cdot ha^{-1}$ in the black cherry-dominated stands (Stands 1, 2) and was 11.5 $m^2 \cdot ha^{-1}$ in the oak-red maple-dominated stand (Stand 3).

The only published silvicultural management guides for hemlock-hardwood stands are based on data from New England (Lancaster 1985) and the Lake States (Tubbs 1977). We followed the relative density targets of the New England guidelines, which recommend that in stands with high relative densities (>46 $m^2 \cdot ha^{-1}$), basal area removal should not exceed more than 1/3 of the total in any given operation (Lancaster 1985). A gradual crown exposure to higher light conditions is more favorable to hemlock physiology and growth response (Mohammed and Parker 1999).

In 2005, prior to timber marking, six 4 ha treatment blocks were established in stand 1, five in stand 2, and eight in stand 3. Half of the treatment blocks in each stand were then randomly assigned to be thinned (note: stand 2 had three thinned and two unthinned blocks) (Fig. 1). Marking guidelines were designed specific to each stand's structural characteristics (e.g., canopy strata), recent ANF inventory data, and relative density guidelines with the general goal to reduce stand density about 30% (Lancaster 1985). Canopy strata are defined as overstory trees, which are in the upper continuous canopy and include dominant, codominant, intermediate, and overtopped crown classes (Smith et al. 1997), and understory tree stems that are at least 2.54 cm diameter at breast height (DBH) with crowns located at least 2 m below the overstory. The treatment was primarily a crown thinning (Smith et al. 1997) to reduce crown competition in the overstory, especially favoring hemlock. We also modified the low-thinning method (Smith et al. 1997) to address the spatial and structural variability of hemlock stems (see fig. 1 in Piatek et al. 2016). For example, in some instances, overstory (overtopped) hardwood trees, such as American beech, were removed because they were shading healthy understory hemlocks with good stem form and LCR > 30%. Additionally, in dense hemlock clusters, trees with <30% LCR, which are less likely to respond to the treatment (Marshall 1927; Smith et al. 1997), were also targeted for removal.

After marking, the goal was to establish 10 0.04 ha circular vegetation sample plots in each treatment block according to a systematic random procedure wherein each block was roughly divided into 10 0.4 ha sections and 1 sample plot randomly located within each section (Fig. 1). In the blocks designated for thinning, a residual hemlock tree that was targeted for canopy release (e.g., has 3–4 surrounding stems marked for removal) served as the plot center. The center trees are referred to as "subject" trees. Similar selection criteria were used to identify 10 hemlocks to serve as subject trees in the untreated blocks. Because stands 1 and 2 had some areas containing wetter soils of the Cavode group, a few blocks had irregular shapes to avoid seasonally wet soils. The ANF utilizes seasonal restrictions or avoidance for harvesting these areas. Additionally, due to the spatial requirements for plot establishment, three blocks ended up with less than 10 sample plots. In stand 1, 1 thinning block had 9 plots, and in stand 2, there were 2 thinning blocks with 8 and 9 plots, respectively, resulting in 90 subject trees/plots in unthinned blocks and 96 in thinned blocks. Commercial thinnings were conducted in winter and spring 2007.

Vegetation sampling

All overstory and understory trees on the 0.04 ha plots were sampled in 2005 (prior to thinning) and again at 5 and 10 years after thinning. Canopy class and species were determined on all plot trees in addition to measuring stem diameter measured at 1.37 m above the ground (DBH). Measurements collected on the subject trees included the following: DBH, total height and height to base of live crown (using a clinometer), and crown width. Base of live crown was measured at the height above ground of the lowest cluster of live branches (Kenefic and Seymour 1999). Crown width was estimated by measuring the length of the longest branch in the four cardinal directions. Observers visually stood under the longest branch and used a Leica DISTO™ to shoot a laser back to the stem and record the distance. After harvesting, we placed permanent stakes at the outer edge of each measurement point to guide future remeasurements.

Analyses

Due to hemlock's irregular crown shape (Kenefic and Seymour 1999), CRAREA on each subject tree was estimated using a slight modification of an ellipse equation: Area = π (ab), where "a" represents the average of the two longest radii and "b" represents the average of the two shortest. LCR is calculated as follows: (total height − height to base of live crown)/total height.

The experiment is set up as a generalized random block design (Kirk 2012) with a repeated-measures factor (Fig. 1). Each stand is considered a fixed variable, because their location was not randomly determined. The 0.4 ha treatment blocks within each stand are considered random variables, because their treatment status was randomly assigned. The repeated-measures factor is the plot/subject-tree remeasurements (time) on the thinned and unthinned treatments. Response variables tested on the subject trees were as follows: DBH, LCR, and CRAREA. Analyses were conducted using the linear mixed-models procedure, and all response variables were first checked for normality (PROC UNIVARIATE procedure) (SAS 9.4, Cary, NC) and then analyzed. Data were also transformed (log and ARCSINE) and tested in the analyses, but it did not improve any of the models.

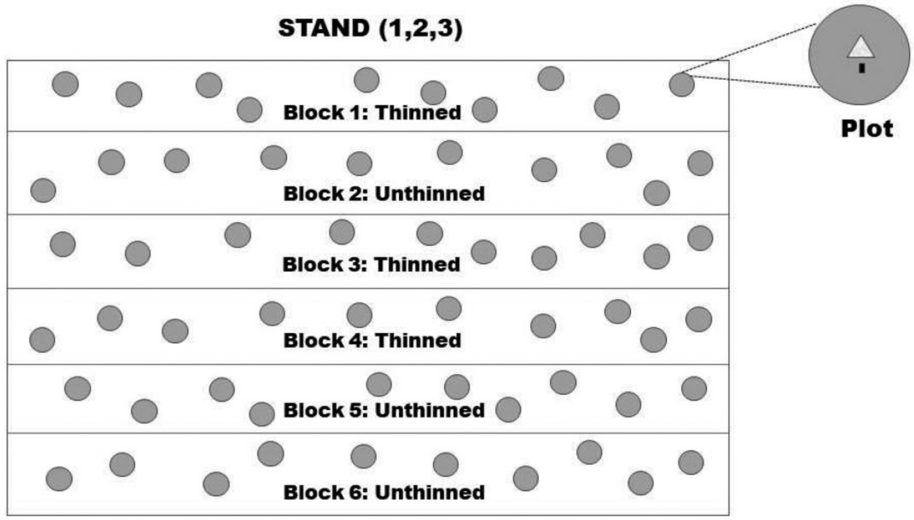
Four covariance structures were modeled using the REPEATED statement in the PROC MIXED procedure (SAS 9.4, Cary, NC) (Fig. 1), with a maximum likelihood estimation set at alpha = 0.05. We first tested unstructured and compound symmetry, which did not converge. The first-order autoregressive covariance structure (AR (1)) and Toeplitz variance components both converged, but AR (1) had a better fit based on the smallest Akaike and Bayesian information criterion diagnostics used to assess the most appropriate model (Burnham and Anderson 2002). Additionally, AR(1) is better suited to temporal data with equally spaced measurement periods and a model assumption that the covariance with previous measurements decreases over time. Post hoc tests on least-squares means were conducted as pairwise comparisons, and all P values were adjusted using the Tukey option. Plot-level basal areas were calculated from live-tree diameters and used as covariates in the models.

Results

Tests of the fixed effects indicated that all response variables had significant temporal, location (stand), and treatment effects. The interactions of stand × time and stand × time × treatment were not significant for all variables, and treatment × time was not significant for DBH. The lack of significance suggested that the slopes were not significantly different from each other across stands for all variables and between treatments for DBH. The basal area covariate was not significant for CRAREA. Basal area × time was not significant for all variables, and basal area × stand was not

Fig. 1. Experimental design layout of treatment blocks in Stand 1: 6, 4 ha blocks (3 thinned, 3 unthinned) and 10, 0.04 ha plots per block centered around 1 subject tree per plot. Stands 2 and 3 had slight modification of this layout (see text). Stands were sampled at Time 1 (pre-thinning in 2005) and 5 and 10 years after thinning.

Experimental Design:



Statistical Model:

$$y_{ijk} = \mu + T_i + L_j + (TL)_{ij} + Y_k + (TY)_{ik} + (LY)_{jk} + (TLY)_{ijk} + e_{ijk}$$

Where:

y= one observation
u = overall mean
T = treatment (Thinned, Unthinned)
L=stand (1,2,3)
Y=time (1,5,10)
TL=treatment*stand interaction
Y=time (1,5,10)
TY=treatment*time interaction
LY=stand*time interaction
TLY=treatment*stand*time interaction
e=error.

SAS Model **(including basal area covariate):**

```
Proc mixed data= datasetname order=data;
Class stand plot treatment time;
Model (Response Variable: DBH or LCR or CRAREA) =stand treatment stand*treatment time
stand*time treatment*time treatment*time*stand basal area basal area*time basal area*stand;
Repeated time/ type = (covariance structure) subject=plot(stand) r r corr;
Run;
```

significant for LCR. All non-significant interactions were removed from additional analyses, and reduced models were produced (Table 1).

In the reduced models, DBH increased over time for all stands and treatments (Fig. 2), with significant stand, time, and treatment effects (Table 1). LCR showed very little temporal change in thinned blocks and significantly decreased in unthinned blocks (Fig. 2). Among stands, LCR in unthinned stand 3 blocks tested no different than thinned blocks in stands 1 and 2.

CRAREA differed among stands and increased over time for both treatments (Table 1), but the magnitude of increase was

Table 1. Probability values for reduced models of type 3 tests of significant fixed effects of the thinning treatment for 3 stands and 3 measurement periods, 5 years apart (time), and their interactions.

Effect	Num DF	Den DF	Pr > F DBH	Pr > F LCR	Pr > F CRAREA
Stand	2	27	0.0020	0.0003	0.0048
Treatment	1	27	<0.0001	0.0083	0.0268
Stand × treatment	2	27	0.0051	0.0055	0.0054
Time	2	58	<0.0001	<0.0001	<0.0001
Treatment × time	2	58		0.0002	0.0003
Basal area	1	508	0.0218	0.0011	0.1698
Basal area × stand	2	508	0.0006		0.0112

Note: Significant fixed effects for variables: diameter (DBH), live crown ratio (LCR), and crown area (CRAREA). Degrees of freedom (DF) for numerator (NUM) and denominator (Den).

greater in thinned blocks (Fig. 2). Means' comparisons among stands indicated that unthinned blocks in stand 2 were significantly lower than thinned blocks in all three stands (*P* values: 0.0349, 0.0109, 0.0005). Within stand 3, unthinned blocks were significantly lower than thinned blocks (*P* value 0.0094).

Temporal trends in stand basal areas increased in unthinned blocks, and there was an increasing post-harvest basal area trend between 2011 and 2016 in thinned blocks (Fig. 3). Basal area was significantly correlated with DBH and LCR, and basal area × stand was significantly correlated with DBH and CRAREA (Table 1).

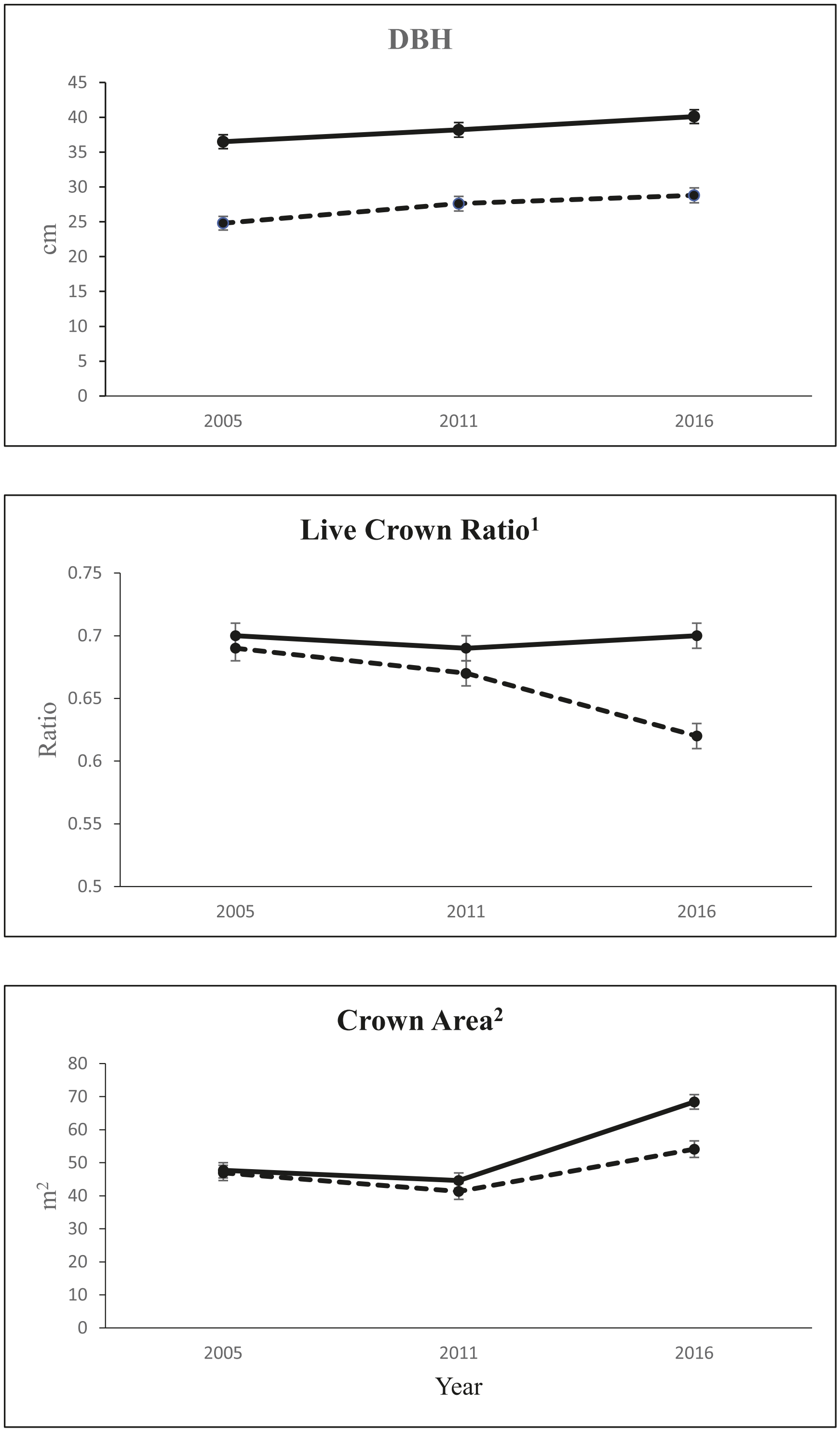
Discussion

After thinning, we monitored individual subject-tree attributes and stand-level basal area changes reported here in addition to other stand growth metrics (in progress). Specific stand-structural attributes guided tree-marking choices in achieving residual basal area goals. Stands were selected based on uniformity of hemlock distribution, basal area, and suitability for thinning according to available management guidelines (Lancaster 1985). Each stand was unique regarding stand history, so the differences among location and treatment were not unexpected. Subject-tree growth increases due to thinning were anticipated, but the rate of increase was questionable, especially because of high initial relative stand densities and only 30% basal area removal. Yet, these dense stands demonstrated improved crown attributes in directly released subject-tree crowns, hence meeting our study objectives.

There was no significant treatment × time interaction for DBH, because diameter increased in both thinned and unthinned stands over 10 years. However, subject trees in thinned blocks averaged a 6.1 (±1.8) cm diameter increase, while the diameter of trees in unthinned blocks increased by 3.4 (±1.3) cm. The slow but positive trend in un-released tree crowns is representative of hemlock's high shade tolerance and steady growth even at high densities (Godman and Lancaster 1990). Additionally, prior to treatment in 2005, most subject-tree crown classifications were dominant/codominant: 93% in unthinned and 76% in thinned. The rest were intermediate with only 1 overtopped (thinned). Dominant and codominant tree crowns receive sunlight from above and some from the sides (Smith et al. 1997) and distribute about 40% of their photosynthesis allocation to xylem production (Assmann 1970). Thinning increases crown-growing space (and other site resources) and results in a temporary acceleration of crown and stem increment before a tree returns to a pre-thinning growth rate as stand density increases (Fajvan et al. 2008). Following crown release from overhead or side shade, hemlock radial growth increment can increase 5%–8% per year, regardless of tree age (Fajvan and Seymour 1993; Marchand and Filion 2014). Even with the targeted crown release in our thinned plots, subject-tree diameter growth increased slowly during the first 5 years. Shade-formed foliage has a limited capacity for photosynthetic acclimation to high light. Therefore, new foliage with enhanced photosynthetic capacity must be produced in the increased light environment (Mohammed and Parker 1999) to increase diameter growth rate.

Maintenance of LCR is one goal of thinning (Smith et al. 1997) and is especially important in reducing vulnerability to HWA (Rentch et. al 2009). Subject trees in thinned blocks generally maintained their LCR over 10 years, while trees in unthinned plots declined after year 5. Eighty-six percent of the unthinned plot trees averaged a 16% LCR decrease, whereas 40% of trees in the thinned group decreased by 10%. Generally, the height growth rate of dominant/codominant trees of a given species is predictable across a range of spacings under similar site conditions. LCR can be considered an index of tree vigor, because crown length is an estimate of the potential photosynthetic surface area when referenced to total tree height (Oliver and Larson 1996). Hemlock is a species with strong epinastic control over lateral shoot development, which affects branch length and crown shape. Side shade can eventually reduce a tree's height growth if it significantly restricts the size of the photosynthesizing crown, such as in an intermediate crown-class tree (Mitchell 1975; Rentch et al. 2009). The total height of subject trees averaged a 1 m increase between measurement periods in thinned plots, was similar during the first period on unthinned plots, and then decreased to 0.4 m between years 5 to 10.

Fig. 2. Temporal and treatment characteristics of 186 hemlock trees sampled from time 1 (pre-thinning in 2005) and 5 and 10 years after thinning. Data presented are least-squares means (± standard errors) for tested variables: diameter (DBH), live crown ratio, and crown area on thinned (solid lines) and unthinned blocks (dashed lines).



[1]Unthinned blocks decreased between years 5-10 and 1-10 (P-values <0.001)

[2]Thinned blocks increased between years 5-10 and 1-10 (P-values <0.001)
and increased in unthinned blocks in the same periods (P-values <0.0001, 0.0040)

Fig. 3. Mean stand basal area estimates (± standard errors) calculated from 0.04 ha plots surrounding subject trees on thinned (solid lines) and unthinned (dashed lines) treatments. Measurements occurred in 2005 (pre-thinning), 2011, and 2016.

Over 10 years, only one subject tree on the thinned plots showed a 3% CRAREA decrease, whereas 16 trees (20%) on unthinned plots averaged a 21% decrease. Unlike some other conifers with geometrically consistent crown shapes (e.g., *Abies balsamea* (L.) Mill.), hemlock crowns are very irregular, especially in large trees (Kennefic and Seymour 1999), and difficult to measure. Our crown radii remeasurements were referenced to a permanent marker and were consistent regarding measurement direction from stem, which provided a relative estimate of temporal crown-width changes. Subject trees were specifically targeted for crown release, so they typically had more growing space directly associated with the crown that did not always reflect the basal area reduction of the associated plot.

When considering the entire stand, we attempted to maintain relatively uniform residual tree spacings in our marking efforts; therefore, not all trees in thinned blocks had direct crown release. Yet, all residual trees benefitted due to stand-density reductions and resulting additional site-resource allocations. However, 6 subject trees died after 5 years in the thinned plots and 10 died in the unthinned plots. Most of the mortality occurred in stand 3, which had comparably drier site conditions, causing more stress to hemlock during summers with low precipitation. Ten years after thinning our data indicate that relative stand densities are increasing and approaching prethinning levels in stand 1 (Fig. 3), indicating the need for additional thinning to maintain growth rates of hemlock crowns.

Even though the original intent of this study was to test a pre-emptive HWA management strategy, we learned that our thinning treatments produced the desired results, which may contribute to future HWA mitigation. Currently, chemical HWA controls are not economically feasible at a forested landscape scale, and biological controls have limited effectiveness (Vose et. al 2013; Mayfield et al. 2015). An integrated management approach combining chemical, biological, and canopy release has been tested at small experimental scales (Brantley et al. 2017; Ford Miniat et al. 2020) and suggests that increased canopy light exposure creates less favorable environments for HWA due to improved crown attributes on released hemlocks. Maintenance of optimal stand density to ensure sufficient crown-growing space could be a contributing factor in reducing future impacts from HWA.

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Data availability

Data generated or analyzed during this study are in the public domain and may currently be accessed from the corresponding author under the USA Freedom of Information Act.

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Data curation: MAF
Formal analysis: MAF
Funding acquisition: MAF
Investigation: MAF, AH
Methodology: MAF
Project administration: MAF, AH
Resources: MAF, AH
Supervision: MAF
Validation: MAF
Writing – original draft: MAF
Writing – review & editing: MAF

Competing interests

The authors declare there are no competing interests.

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