An Assessment of Eastern Hemlock Crown Dynamics 10-years After Thinning on the Allegheny Plateau, Pennsylvania

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Abstract.—Hemlock woolly adelgid (HWA) threatens the existence of eastern hemlock trees and associated ecosystems. We propose that increasing canopy light exposure via silvicultural thinning can reduce hemlock's vulnerability to HWA. Four, overstocked stands on the Allegheny National Forest were selected for thinning. There was no HWA infestation and half of each stand was thinned. Thirty circular plots per stand were established surrounding a hemlock targeted for crown release on 3 to 4 sides. Similar criteria were used to select hemlocks in 30 untreated plots. We visited subject trees prethinning, and 5 and 10 years post thinning; diameter, total height, live crown ratio, and crown area were measured on 246 trees. 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.

INTRODUCTION

Eastern hemlock (*Tsuga canadensis* (L.) Carr.) 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, Witt and Webster 2010).

The hemlock woolly adelgid, (HWA, *Adelges tsugae* Annand) is a major threat to forest ecosystem health and economic viability of eastern North American hemlock species—eastern hemlock and Carolina hemlock (*Tsuga caroliniana* Engelm.) (Knauer et al. 2002). Since its introduction in the 1950s, HWA has spread approximately 5 to 20 miles/ year (Evans and Gregoire 2007, Morin et al. 2009), infesting 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). Hemlock in dominant and codominant overstory crown class positions appear to survive HWA longer than intermediate and overtopped crown class trees (Eschtruth et al. 2006, Onken 1996, Orwig and Foster 1998). 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 (Rentch et al. 2009). Infested hemlocks with crowns receiving full sunlight, such as those growing along forest edges or

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in gaps, appear to survive longer than trees growing in shade. Higher light (Brantley et al. 2017, Hickin and Preisser 2015, Lapham et al. 2018) and temperature (Sussky and Elkinton 2015) may negatively affect HWA survival and promote new shoot growth (Ford Miniat et al. 2020, McAvoy et al. 2017).

Silvicultural manipulations that reduce stand density alter forest climate and soil and foliar nutrient cycles (Van Cleve and Zasada 1976). Thinnings reallocate fixed resources among fewer stems increasing the amount of light, water, and nutrients per tree and enhancing growth. 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 (Fajvan 2008, Knauer et al. 2002, Waring and Pitman 1985).

The effectiveness of silvicultural treatments for improving resource acquisition and tree health in mixed-species hemlock stands has not been extensively studied. There are few thinning studies in mixed-hemlock stands containing a significant hemlock component (>30 percent basal area) (Fajvan 2008), that focus on reducing stand density specifically to favor hemlock growth. Hemlock height and diameter growth after crown release is related to preharvest stand density and canopy status (overstory vs. understory) (Marshall 1927, Merrill and Hawley 1924). Trees growing in dense stands showed 60 percent greater growth after thinning (from above and below) than stands that were understocked. Hemlocks previously growing in suppressed canopy positions tend to have better stem form and faster growth after release than open-grown associates of similar size. 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 (Fajvan and Seymour 1993, Marshall 1927).

Relationships of HWA Biology with Hemlock Physiology

HWA's complex reproductive cycle produces two asexual generations per year: the spring "progrediens," and overwintering "sistens," which take advantage of hemlock's winter physiological activity. In both generations, first instar "crawlers" settle on twigs, insert their stylets into the underside of the needle base, and feed on nutrients stored in xylem ray parenchyma cells (Havill et al. 2014, Young et al. 1995). The prolonged winter feeding of the sistens generation allows it to tap into a tree's stored food in the absence of any potential predators. The xylem ray parenchyma cells play an important functional role in transpiration solute and carbohydrate storage, and transport and storing of water reserves. HWA-caused carbohydrate depletion from these cells can impact both carbon and water cycling and may be most apparent in trees that already have a marginal carbon balance (Secchi et al. 2017), such as hemlocks in intermediate crown class positions (Rentch et al. 2009).

High densities of HWA deplete food reserves and diminish a tree's ability to produce new foliage (Evans 2002). HWA is chronic in nature and effects are not immediate. Trees with low HWA populations tend to have larger percentages of nymphs in the upper crown whereas heavily infested trees have more nymphs in the lower crown (Evans and Gregoire 2007). Subsequent needle discoloration, premature needle drop, branch tip dieback, and foliage thinning causes growth decline (Rentch et al. 2009) and can result in tree mortality ranging from almost none to 95 percent (Bair 2002, Mayer et al. 2002, Orwig and Foster 1998). Stand-level mortality can occur quickly and uniformly, especially in the presence of other stressors or can occur slowly and in patches for more than a decade.

Use of Silvicultural Thinning in HWA Management

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).

We initiated a study in 2005 to determine if stand structure manipulations can be used ahead of the leading edge of HWA invasion to improve individual host tree and stand resistance. Specifically, we designed thinnings to reduce relative stand density in fully stocked and overstocked hemlock-hardwood stands (Lancaster 1985) 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 increase live crown ratio (LCR), crown area (CRAREA), and diameter prior to HWA arrival. Four Pennsylvania stands were thinned in 2007 and have been monitored for 10 years however, there has been no HWA infestation to date. In this paper we present the findings from the intensive monitoring of crown attributes for 246 "subject" trees, half of which received direct crown release on 3 or 4 sides in thinned plots. We compare the changes in growth parameters between trees with released crowns and those without.

METHODS

Study Area and Treatment

Thinnings were conducted in four, 24-ha stands selected on the Allegheny National Forest (ANF) in northwestern Pennsylvania near the town of Warren (41.64976°N, 79.03913°W). The forest covers about 210,000 ha and is 90 percent forested with an average elevation of 427 m. Soils in the project area belong to two main soil groups: Cavode silt loams with 0 to 8 percent slope, and Cookport very stony silt loams, with 0 to 15 percent slope. Vegetation consists of second-growth, 70- to 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* Britt.), northern red oak *(Quercus rubra* L.*)*, sugar maple (*Acer saccharum* Marsh), and American beech (*Fagus grandifolia* Ehrh.). Hemlock is found either in pure patches or dispersed within the hardwoods. The ANF has a moderate climate, with warm and humid summers. Average temperatures range from 23.9 to 26.7 °C (75 to 80 °F) in summer to -3.9 to -6.7 °C (20 to 25 °F) in winter and mean annual precipitation ranges from 889 to 1,295 mm (USDA Forest Service 2018). All stands were located on the ANF Bradford Ranger District; three in compartment 301 and one in compartment 341.

Stand size was determined based on feasibility of conducting a commercial harvest. Required hemlock content was a minimum basal area of 7 m^2/ha. The three stands in compartment 301 were overstocked with total basal areas ranging from 39 to 46 m^2/ha. 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/ha in the black cherry-dominated stands (Stands 1, 2) and from 7 to 11.5 m^2/ha in the oak-red maple – dominated stand (Stand 3). Stand 4 was fully stocked at 23 m^2/ha with 8 m^2 ha^{-1} hemlock and 33 percent of hemlock stems <13 cm d.b.h. (diameter at 1.37 m above ground). The overstory was composed of red maple, black birch, and

American beech. Clumps of noncommercial sized hemlocks were thinned with brush saws and left on site in Stand 4.

The only published silvicultural thinning guidelines for hemlock-hardwood stands are based on data from New England and the Lake States (Lancaster 1985, Tubbs 1977). We followed the stocking targets of the New England guidelines, which recommended removal of at least 6 to 7 m^2/ha of basal area; however, if stands are very dense (>46 m^2/ha), basal area removal should not exceed more than one-third of the total in any given operation (Lancaster 1985).

In 2005, prior to timber marking, six 4-ha treatment blocks were established in each stand. Three of the treatment blocks were then randomly assigned to be thinned. Marking guidelines were designed specific to each stand's structural characteristics, recent ANF inventory data, and stocking guidelines with the general goal to reduce relative stand density 30 to 40 percent (Lancaster 1985). The treatment is primarily a crown thinning to reduce crown competition however, low thinning (Smith et al. 1997) criteria were also incorporated, especially in the compartment 341 stand, to address the spatial and structural variability of hemlock stems. In some instances, hardwood trees were removed because they were overtopping hemlocks with good stem form and LCR >30 percent. In dense hemlock clusters trees with <30 percent LCR, which are less likely to respond to the treatment (Marshall 1927, Smith et al. 1997), were targeted for removal.

After marking, ten 0.04-ha circular vegetation sample plots were located in each treatment block according to a systematic random procedure wherein each block was roughly divided into ten 0.4-ha sections and one sample plot randomly located within each section. In the blocks designated for thinning, a residual hemlock tree that was targeted for canopy release (e.g., has three to four 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 totaling 60 per stand. Commercial thinnings were conducted in winter and spring 2007.

Vegetation Sampling

All overstory and understory trees on all 0.04-ha plots were sampled in 2005 (prior to thinning) and again at 5 and 10 years after thinning. Overstory trees are those in the B-stratum (upper continuous canopy) and include dominant, codominant, intermediate, and overtopped crown classes (Smith et al. 1997). Understory trees are those stems that are at least 2.54 cm d.b.h. with crowns located at least 2 m below the overstory. Canopy class and species were determined on all plot trees in addition to measurements of height class (3 m increments up to >15.24 m) and d.b.h. In 2005, all overstory trees were visually classified according to crown class. Measurements collected on the subject trees included: d.b.h., 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 branches (Kenefic and Seymour 1999). Crown width was estimated by measuring the length of the longest branch in four cardinal directions. Observers visually stood under the longest branch and used a Leica DISTO^{TM} to shoot a laser back to the stem and record the distance. In 2005, observers placed permanent stakes at 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:

$$Area = \pi (ab)$$

where

a represents the average of the two longest radii, and

b represents the average of the two shortest radii.

LCR is calculated as: (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. Each of the four stands is considered a fixed variable because their location was not randomly determined. The six 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 remeasurements (time) on the thinned and unthinned treatments. Response variables tested on the subject trees were d.b.h., LCR, and CRAREA.

All analyses were conducted using the linear mixed models procedure (SAS 2018), and covariance structures were modeled using the REPEATED statement in the PROC MIXED procedure, with a maximum likelihood estimation set at alpha=0.05. Even though the data are temporal, with only three measurement periods the simplest correlation model of compound symmetry provided the best fit to the data. The model assumption is that correlation is constant regardless of the time between points. Post-hoc tests on least squares means were conducted as pairwise comparisons, and all *P* values were adjusted using the Tukey option.

RESULTS

Tests of the fixed effects indicated that all response variables had significant temporal, location (stand), and treatment effects (Table 1). The interaction of stand × time was not significant for either d.b.h. and LCR, and treatment × time was not significant for d.b.h. The lack of significance suggested that the slopes were not significantly different from each other across stands for both variables, and between treatments for d.b.h. Hence both interaction terms were dropped from the d.b.h. model and stand × time was dropped from the LCR model (Table 2).

Comparisons of least squares means of the new models (Table 2) indicated that even though d.b.h. showed overall significant stand and time effects, there were no temporal differences among stands or treatments. Both control and thinned stands increased in diameter over time and for all stands (Table 3). Comparisons of the least squares means showed d.b.h. among control blocks was significantly lower in Stand 2 compared to Stand 1 (P-value 0.0008) and higher in Stand 2 compared to Stand 4 (P-value 0.0001). Among thinned block comparisons, Stand 4 d.b.h was significantly lower than both Stand 1 (P value 0.0002) and Stand 2 (P-value 0.0001).

LCR had a significant stand × treatment effect (Table 2) and all stands had significantly higher LCR in thinned stands (P-value <0.0001). LCR also had a significant treatment × time effect (Table 2) but comparisons of least squares means showed no significant differences among thinned blocks between years 1 and 5, 5 and 10, and 1 and 10. For control blocks, LCR significantly decreased between years 1 and 10 (P value <0.0001) and years 5 and 10 (P value < 0.0001) and was unchanged between years 1 and 5 (Table 3).

Table 1.— Linear mixed model Type 3 tests of the fixed effects variables: Diameter (d.b.h), LCR (live crown ratio), and CRAREA (crown area)

		Pr >F	Pr >F	Pr >F
Effect	DF	DBH	LCR	CRAREA
Stand	3	0.0131	<0.0001	<0.0001
Treatment	1	<0.0001	<0.0001	0.0303
Stand×Treatment	3	<0.0001	0.0002	<0.0001
Time	2	<0.0001	<0.0001	<0.0001
Stand×Time	6	0.9927	0.9339	0.0089
Treatment×Time	2	0.2978	<0.0001	0.0003

Table 2.— Linear mixed model Type 3 tests of the fixed effects variables diameter (d.b.h) and LCR (live crown ratio) after interaction terms Stand × Time and Treatment × Time (just for diameter) were removed from original models

		Pr >F	Pr >F
Effect	DF	d.b.h.	LCR
Stand	3	0.0070	<0.0001
Treatment	1	<0.0001	<0.0001
Stand×Treatment	3	<0.0001	0.0002
Time	2	<0.0001	<0.0001
Stand×Time	6	n/a	n/a
Treatment×Time	2	n/a	<0.0001

Table 3.—Temporal and treatment characteristics of 246 hemlock trees sampled from Time 1 (prethinning in 2005) and Times 5 and 10 years after thinning in 2007. Data presented are least squares means (+standard errors).

	Treatment					
	Control			Thinned		
Time	1	5	10	1	5	10
d.b.h. (cm)	27.9 (0.79)	30.0 (0.79)	31.2 (0.81)	32.8 (0.76)	35.6 (0.76)	38.4 (0.76)
Live crown ratio	0.67 (0.01)	0.65 (0.01)	0.59 (0.01)	0.68 (0.01)	0.67 (0.01)	0.68 (0.01)
Crown area (m^2)	44.1 (1.8)	41.4 (1.8)	51.6 (1.9)	41.6 (1.7)	42.2 (1.7)	62.8 (1.7)

CRAREA also had a significant overall stand × treatment effect with only Stand 4 showing no difference. There were also no significant differences between years 1 and 5 for either treatment but CRAREA increased for both treatments between years 5 and 10 (P values <0.0001) and 1 and 10 (control P-value 0.0035 and thinned <0.0001), although, the degree of increase over 10 years was greater in thinned blocks (Table 3).

DISCUSSION

Even though the original intent of this study was to test a preemptive HWA management strategy, we did learn that our thinning treatments produced the desired results, which could serve to mitigate HWA survival in the future. Currently, chemical HWA controls are not economically feasible at a forested landscape scale and biological controls have limited effectiveness (Mayfield et al. 2015, Vose et.al 2013). 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.

Our harvests were conducted at a commercial scale, yet we monitored both individual subject tree attributes, reported here, and also modeled stand-level growth (results 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 stocking criteria. 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 the high initial density of Stands 1, 2, 3 (Compartment 301) with only one-third basal area removed. Yet, these three overstocked stands demonstrated improved crown attributes in directly released subject tree crowns. Hence meeting the objectives of the study.

There was no significant treatment × time interaction for d.b.h. because diameter increased in both thinned and unthinned stands over 10 years even though subject trees in thinned blocks increased an average of 6.1 (± 1.8) cm while control trees increased 3.3 (±1.3) cm. The slower trend in control trees is representative of hemlock's high shade tolerance and steady growth even at high densities. Hemlock diameter responds slowly to partial canopy disturbances, especially after growth suppression, resulting in stands with highly variable individual tree growth rates (Fajvan and Seymour 1993).

Tree crown variables also responded positively to thinning. Eighty-seven percent of the unthinned trees averaged 18 percent LCR decreases and all trees in the thinned group increased an average of 7 percent. Subject trees in thinned blocks generally maintained their LCR over 10 years as control trees declined after year 5. 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). All thinned trees showed some degree of CRAREA increase whereas only 8 percent of unthinned trees increased. Prior to treatment in 2005 most subject tree crown classifications were dominant/codominant: 90 percent in control and 77 percent in thinned. The rest were intermediate with only one overtopped (thinned). Stand 4 (Compartment 341), was the only stand that showed no treatment difference for CRAREA and as expected, it had significantly lower average diameters for all measurement periods. Initially this stand was structurally very different from the others with about half of the preharvest basal area and much smaller diameter hemlocks. Hence, most of the crown competition was in the mid-story hemlock clusters that were thinned. The overstory subject trees in that stand probably did not experience as dramatic a crown release as the other stands because the stand had much lower initial stocking.

When considering the entire stand, we attempted to maintain relatively uniform residual tree spacing 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 site resource allocations. Ten years after thinning, our data indicate that relative stand density has increased enough to warrant a second thinning, or initiation of the shelterwood sequence, to sustain growth of released hemlock crowns. Maintenance of sufficient crown growing space will be a contributing factor in minimizing future impacts from HWA.

ACKNOWLEDGMENTS

This project is a partnership between the USDA Forest Service Northern Research Station, Morgantown, WV, and the Allegheny National Forest, Warren, PA. We thank all of the Forest Service foresters who have been involved in field data collection throughout the study.

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CITATION: Fajvan, Mary Ann; Hille, Andrea T. 2023. **An Assessment of Eastern Hemlock Crown Dynamics 10-years After Thinning on the Allegheny Plateau, Pennsylvania.** In: Kern, Christel C.; Dickinson, Yvette L., eds. Proceedings of the first biennial Northern Hardwood Conference 2021: Bridging science and management for the future. Gen. Tech. Rep. NRS-P-211. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station: 136–146. https://doi.org/10.2737/NRS-GTR-P-211-paper28.