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AN ANALYSIS OF THE INFLUENCES ON EASTERN HEMLOCK SUCCESSION IN THE AFTERMATH OF HEMLOCK WOOLLY ADELGID INFESTATION IN NOVA SCOTIA, CANADA

by

Hannah A. D. LeBlanc

A thesis submitted in fulfillment of the
requirements of BEST 4599
for the Degree of Bachelor of Environmental Studies (Honours)

Bachelor of Environmental Studies Program
Saint Mary's University
Halifax, Nova Scotia, Canada

April 2025

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ABSTRACT

An Analysis of the Influences on Eastern Hemlock Succession in the Aftermath of Hemlock Woolly Adelgid Infestation in Nova Scotia, Canada

by

Hannah A. D. LeBlanc

This study investigates the impact of Hemlock Woolly Adelgid (HWA) infestation on eastern hemlock (*Tsuga canadensis*) forest succession in Nova Scotia, Canada, with a focus on stand dynamics, tree health, and early successional trends. By comparing heavily defoliated stands in the Southern region with less affected or unaffected stands in Central Nova Scotia, significant regional differences in structure and composition were observed—largely attributable to climatic and ecological variation between ecoregions. HWA presence was strongly associated with increased snag density and downed woody debris (DWD) volume, indicators of widespread hemlock mortality. However, eastern hemlock remains a dominant species across all plots, suggesting resilience in the short term. Results of this research highlight the urgent need for targeted conservation strategies, long-term monitoring, and forest management practices.

April 2025

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Introduction

1.1. Background

The province of Nova Scotia is embedded in the unique and biodiverse Acadian Forest ecosystem, expanding across the Maritime provinces of Canada, and acting as an ecological transition zone between the boreal forests to the north and the temperate deciduous forests to the south (Taylor *et al.*, 2017). Although largely dominated by the Acadian Forest, the Maritime Boreal Forest is also a common feature of Nova Scotia's landscape, however, its range is almost entirely limited to geographical regions with high elevations and cooler coasts. Together, these two forest types are estimated to cover nearly 76 per cent of the province's land area and expand across diverse ecosystems, ranging from fertile wetlands to dry rock outcrops and present at various elevations (Neily *et al.*, 2023). The more temperate Acadian Forest is dominated by red spruce (*Picea rubens*), with other common species including sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), yellow birch (*Betula alleghaniensis*), American beech (*Fagus grandifolia*), white ash (*Fraxinus americana*), red oak (*Quercus rubra*), eastern hemlock (*Tsuga canadensis*), red pine (*Pinus resinosa*), and eastern white pine (*Pinus strobus*) (Taylor *et al.*, 2017).

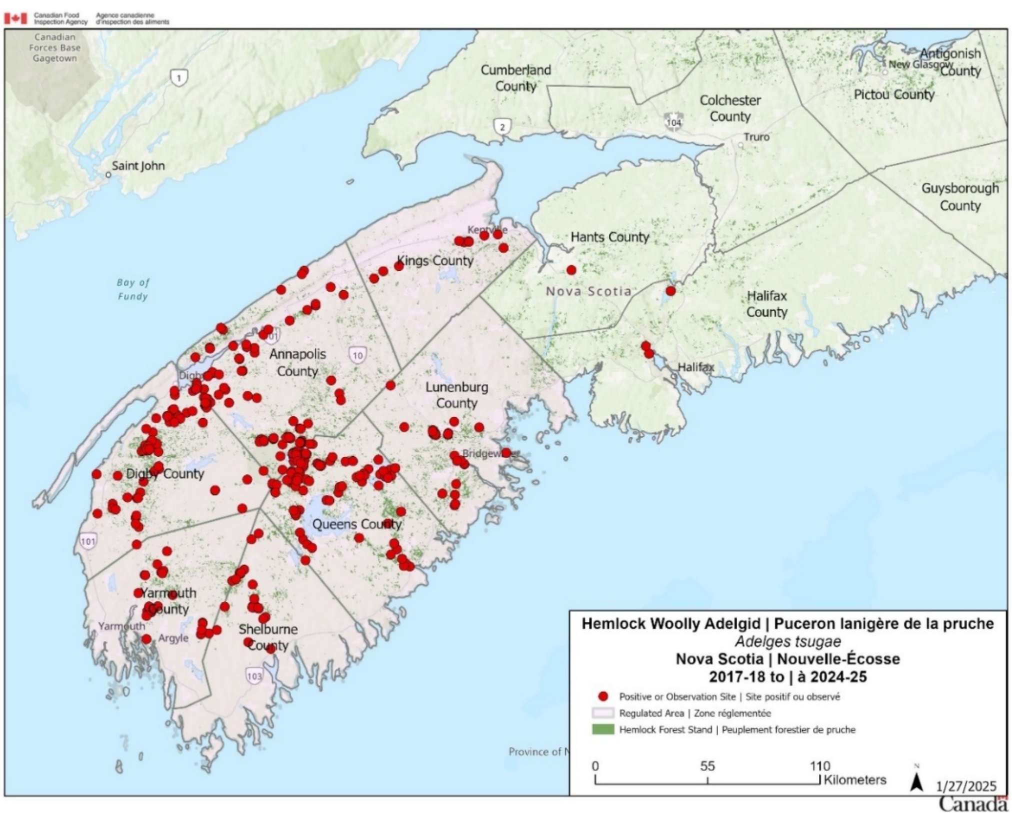
Although it is densely populated by red spruce, the Acadian Forest ecosystem largely depends on a single keystone species, the eastern hemlock, to produce structural diversity and support habitats for a variety of vertebrate and arthropod species, in addition to balancing core ecosystem process involving energy, nutrient, and water flows (Degrassi *et al.*, 2019). Further, the ecological functioning of eastern hemlock stands contributes to ecosystem balance and stability, forming a unique microclimate that supports more than 120 wildlife species (Ulnooweg Education Centre, n.d.). Although eastern hemlock is a common and very important tree species, especially in Nova Scotia's Acadian Forests, populations are quite dispersed and typically account for ≤10% of crown coverage when present (Maclean *et al.*, 2021). Eastern hemlock is a late-successional, highly shade-tolerant coniferous species native to North American, with a geographical range extending well over 10,000 km^2. Late-successional species are slow-growing, long-lived, and highly competitive, capable of growing in ecosystems with limited resource availability. Many of Nova Scotia's eastern hemlocks predate the European colonization of Canada, able to survive for hundreds of years. Further, the species is recognized for its influences on old-growth forest structure and ecosystem functioning (Ellison *et al.*, 2018; Orwig & Foster, 1998; Vose *et al.*, 2013). For example, eastern hemlocks provide shade to cool streams, meanwhile, creating a critical year-round habitat for bird species and other animals that require plenty of canopy cover to survive. With shallow roots and relatively thin bark, eastern hemlocks are particularly sensitive to natural (i.e., wind, fire, and drought) and anthropogenic disturbances (Orwig & Foster, 1998).

1.2. Hemlock Woolly Adelgid in Nova Scotia

1.2.1. Cause & Effect

The Acadian Forests of Nova Scotia are currently facing threats of significant change to forest stand dynamics due to the amplification of large-scale, stand-replacing natural disturbances induced by climate change. Since its discovery in Virginia in 1951, the invasive insect species, hemlock woolly adelgid (*Adelges tsugae*, HWA), has devastated both eastern hemlock and Carolina hemlock (*Tsuga caroliniana*) stands throughout the eastern United States (Emilson & Stastny, 2019, p. 327). It is believed that the non-native, aphid-like pest was accidentally introduced to the eastern United States from Asia in the 1950s, with its originating lineage tracing back to Japan (Vose *et al.*, 2012, p. 210; Ellison *et al.*, 2018, p. 1, Emilson & Stastny, 2019, p. 327). HWA was only just detected in the southwestern part of Nova Scotia in 2017, although, it is suspected that the invasion had already been well underway by that time, as significant eastern hemlock decline and mortality had evidently occurred by that time (Emilson & Stastny, 2019, pp. 327-328). Figure 1.1 below is a map of southern counties in Nova Scotia which are regulated for HWA as of January 2025, and shows the distribution of confirmed HWA sightings in the province.

Figure 1.1 Map of southern Nova Scotia highlighting counties regulated for HWA as of January 2025



The distribution of provincial eastern hemlock stands is depicted in green, with HWA observation plots depicted using red dots (CFIA, 2025).

As winters continue to become warmer, HWA can expand its range into the northern parts of the province, overwintering, or becoming dormant during the Winter season to enhance its survivability into the Spring (Ellison *et al.*, 2018). HWA aggressively attacks eastern hemlock foliage, attaching itself at the base of hemlock needles before inserting a piercing mouthpart to extract vital nutrients from its host tree. Once all the nutrients have been extracted, the needles will decay and the tree will lose its capacity to photosynthesize and produce nutrients to feed from, often resulting in mortality (Vose *et al.*, 2012). This invasive pest presents a wide variety of challenges for the eastern hemlock, causing a lethal amount of ecological stress on individual trees, stands, and entire forests, ultimately affecting every organism in its surroundings. Further concerns exist for mature and old-growth stands, as dead hemlock trees are expected to block paths and roadways, presenting increased risks to public safety (Vose *et al.*, 2013, as cited in Emilson & Stastny, 2019).

1.2.2. Future Succession & Stand Dynamics

HWA is expected to shift forest stand dynamics within the Acadian Forest, as new forms of regeneration will act to restore ecosystems that have been decimated, altering their vegetation structure and composition. Based on forecasting from ecosystem models of adelgid-driven hemlock dynamics, current predictions suggest that hemlocks will be replaced with early successional hardwood species within a decade (Ellison *et al.*, 2018). As eastern hemlocks become defoliated and the canopy cover thins, different vegetation types will gain competitive advantages over species adapted to cooler temperatures and shade (Oliver & Larson, 1996). Although an array of research exists regarding the successional pathways of forests in the eastern United States following HWA infestation, the recent discovery of HWA in Nova Scotia calls for new, more relevant research pertaining to the Acadian Forest region. Accurate successional observations and modeling would require several years worth of data, which is not currently available for Nova Scotia due to the more recent discovery of HWA in the province and the prematurity of seedling regeneration. Additionally, successional modeling methods often rely on the unrealistic assumption that environmental conditions will remain the same from one site to another, such as with chronosequencing, which differentiates each site in a sequence based only on age (Johnson & Miyanishi, 2008).

1.2.3. Research Objectives

My analysis will focus on linking recently collected site condition data to past disturbance events to aid in identifying the successional pathway of dead and dying eastern hemlock stands in the aftermath of HWA infestation in Southwestern Nova Scotia. This exploratory and inferential analysis will be guided by the following research objectives:

1. To explore and compare forest structure and composition across treatment types; and
2. To explore and compare regeneration opportunities of tree species across treatment types to predict successional forest pathways for defoliated stands.

CHAPTER 2

Methods

2.2. Field Methods

2.2.1. Site Selection

Site selection occurred early in 2024 as part of a collaborative HWA chemical treatment program between the Canadian Forest Service (CFS) and the Nova Scotia Department of Natural Resources (DNR), for the purpose of assessing fuel structure in old-growth eastern hemlock dominated stands of Nova Scotia (Chavardès *et al.*, 2025). 15 old-growth stands dominated by eastern hemlock (composition in the dominant layer ≥50%, mean DBH of dominant trees ≥30 cm) were selected to capture the gradient of HWA impacts in Southern and Central Nova Scotia, with additional plots established at the recorded edge of the HWA infestation during 2024 to assess the effect of chemical insecticide treatment (Quinterno et al. 2023, as cited in Chavardès *et al.*, 2025). In the Fall of 2024, a ground treatment of imidacloprid was administered to the basal area within five plots; however, these plots were excluded from the present analysis as insufficient time has passed to observe measurable treatment effects.

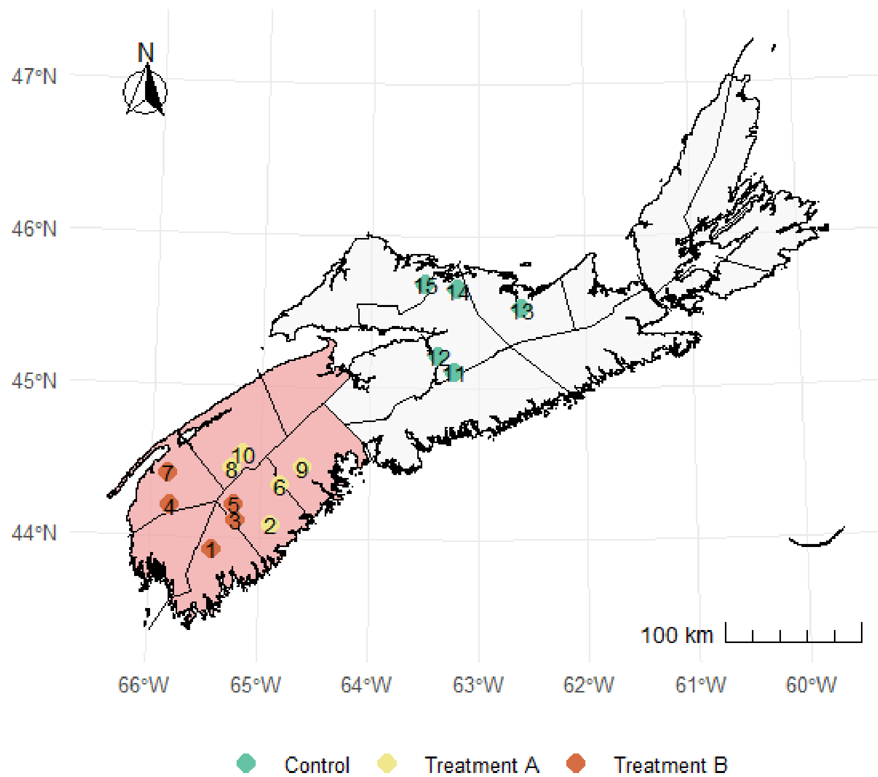
Hereafter, 'treatment' refers exclusively to plots assigned to one of the following experimental conditions (Table 2.1):

1. untreated and heavily defoliated (n = 5);
2. untreated and light to moderately defoliated (n = 5); or
3. HWA undetected (n = 5).

Table 2.1 Treatment conditions defined by defoliation level caused by HWA

Region	Treatment Condition	Defoliation Category	Sample Plots (n =)
Central	Control	Undetected	5
Southern	Treatment A	Moderate – light	5
Southern	Treatment B	High	5

Figure 2.1 Selected old-growth eastern hemlock dominated stands in Nova Scotia (n = 15)



Counties in Nova Scotia that recorded hemlock woolly adelgid infestations in 2024 are shown in light red (adapted from Edge *et al.*, 2025).

2.2.2. Site Information

Site attributes were measured upon site selection, including the coordinates at plot centre, elevation above sea level (m.a.s.l.), aspect, slope (%), soil drainage, texture, and topography (Table 2.2). These features provide insight into the regional variations and similarities between plots, such as moisture and nutrient regimes.

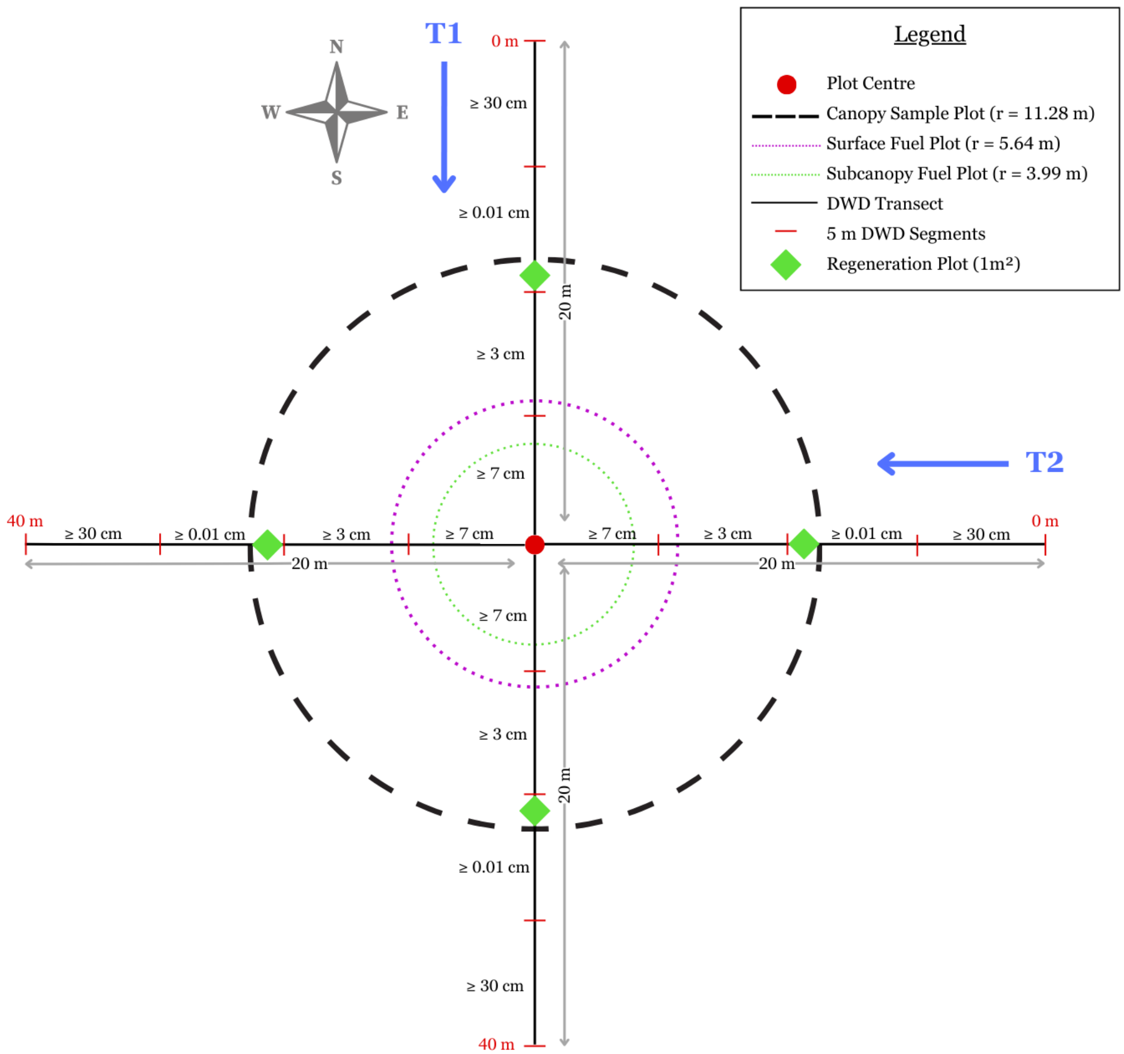
Table 2.2 Site information

Site ID	Treatment Condition	Latitude	Longitude	Elevation (m.a.s.l.)	Aspect	Slope (%)	Soil Drainage	Texture	Topography
1	Treatment B	43.9196	-65.4278	79	NE	2	Well drained	Medium	Hummocky
2	Treatment A	44.08764	-64.8942	99	S	2	Imperfectly drained	Medium	Smooth/Flat
3	Treatment B	44.11158	-65.2213	92	NE	6	Well drained	Medium	Drumlinoid
4	Treatment B	44.20208	-65.8211	71	SW	8	Well drained	Medium	Hummocky
5	Treatment B	44.21567	-65.243	89	E	3	Well drained	Medium	Hummocky
6	Treatment A	44.34633	-64.8106	85	W	10	Well drained	Medium	Drumlinoid
7	Treatment B	44.41738	-65.8526	76	S	25	Well drained	Medium	Drumlinoid
8	Treatment A	44.45615	-65.268	126	W	6	Well drained	Medium	Hummocky
9	Treatment A	44.46558	-64.6197	45	W	3	Well drained	Medium	Drumlinoid
10	Treatment A	44.55392	-65.1547	160	E	0	Well drained	Coarse	Hummocky
11	Control	45.10612	-63.2243	116	NW	7	Well drained	Medium	Hills
12	Control	45.21133	-63.3719	61	SW	10	Imperfectly drained	Fine	Hummocky
13	Control	45.5215	-62.5958	134	SE	21	Well drained	Fine	Hills
14	Control	45.64622	-63.197	55	N	4	Well drained	Coarse	Hummocky
15	Control	45.68509	-63.4869	57	NE	4	Imperfectly drained	Fine	Ridges

2.2.2. Sampling Design, Parameters & Data Collection

All of the field data collection in this analysis was collected by the CFS and DNR, following the protocol outlined in the Field Guide: Sampling Fuels in the Context of the Next-Generation Canadian Forest Fire Danger Rating System (Boucher *et al.*, 2024, as cited in Chavardès *et al.*, 2025). A fuels sampling plot was established within each of the 15 old-growth stands dominated by eastern hemlock, with 5 sampling plots for each treatment condition. For each plot centre point, the geographic coordinates, ellipsoidal height, and elevation above sea level were obtained using a SXblue II Global Navigation Satellite System (SXblue GPS Inc. 2017). Slope and aspect were extracted for each plot using a GIS and Light and Detection Ranging (LiDAR) derived digital elevation model (GeoNova 2024, as cited in Chavardès *et al.*, 2025). Soil drainage and texture classes, topographic pattern and landform class were obtained at each plot from the provincial Ecological Land Classification (Nova Scotia Department of Natural Resources and Renewables 2023, as cited in Chavardès *et al.*, 2025). At each plot centre point, a Canopy Fuel Plot (circular plot r = 11.28 m, area = 400 m^2), a Subcanopy Fuel plot (circular plot r = 3.99 m, area = 50 m^2), and a Surface Fuel Plot (circular plot r = 5.64 m, area = 100 m^2) was established, as represented in Figure 2.2 (Chavardès *et al.*, 2025).

Figure 2.2 Diagram of sample plot structure



Plot layouts for canopy, surface fuel, subcanopy, and regeneration plots, including 20 m DWD transects in each cardinal direction (T1 = 40 m N to S; T2 = 40 m E to W). Adapted from Figure 1 (Boucher *et al.*, 2024, p. 7).

Within each Canopy Fuel Plot, all trees with a height ≥1.3 m and a DBH ≥9 cm were tagged, and their species, DBH, distance from plot centre and azimuth, state (alive, dead with needles, dead without needles, or other), stem condition (intact or broken), bark condition (intact, peeling, or completely gone), presence or absence of lichen, and total height was recorded (the state 'other' meaning snags). For all conifers with a DBH ≥9 cm, live crown base height (LCBH) and dead crown base height (DCBH) were measured as well. Within each Subcanopy Fuel Plot, the species, DBH, state, stem condition, bark condition, presence or absence of lichen, and total height of all trees with a height ≥1.3 m and a DBH <9 cm was recorded. For these trees, LCBH and DCBH were also measured for all conifers. Snags with a vertical lean >45° were characterized as downed woody debris (DWD) and tallied. Within each Surface Fuel Plot, the species and percent cover of surface fuel shorter than 1.30 m (i.e., low shrubs, herbs, bryoids, and litter) was recorded (see Table 2.3) (Chavardès *et al.*, 2025).

Table 2.3 Surface fuel layers defined

	Definition
Low shrubs	Woody perennial plants shorter than 1.30 m, having multiple stems that branch from the base without a well-defined main stem.
Herbs	All herbaceous species, including forbs (including ferns and fern allies), grasses, sedges, and rushes.
Bryoids	Mosses, sphagnum, liverworts, hornworts, and non-crustose lichens.
Litter	Leaf and needle litter layers on top of the bryoid layer.

Adapted from Boucher *et al.*, 2024.

To measure DWD, two 40 m transects were measured from North-South (T1) and East-West (Tt 2), intersecting at plot center (Boucher *et al.* 2024, as cited in Chavardès *et al.*, 2025). The species, decomposition class, position (touching the ground or elevated), tilt angle, and diameter were recorded for all DWD pieces >30 cm crossing each transect, representing the logs with the most significant influence on nutrient cycling and structural diversity (Joyce *et al.*, 2018). Each transect was separated into 8 segments, in which DWD was measured at different diameter classes (e.g., segments 2 and 7 measured at ≥0.01 cm, segments 3 and 6 measured at >3 cm, and segments 4 and 5 measured at 7 cm) (Table 2.4, Boucher *et al.* 2024, as cited in Chavardès *et al.*, 2025). Therefore, fine woody debris (diameter ≥0.01 and ≤1.00 cm) was tallied at segments 2 and 7, and small woody debris (diameter >1.00 cm and ≤3.00 cm) was tallied at segments 3 and 6. The species of coarse woody debris (diameter >3.00 cm) was identified, alongside its position (i.e., E = elevated and G = touches ground) and tilt angle, and its level of decomposition (i.e., 1 = intact, hard, 2 = intact, hard to partly decaying, 3 = hard, large pieces, partly decaying, 4 = small, blocky pieces, and 5 = many small pieces, soft portions) (Table 2.5).

Table 2.4 DWD transect measurements

Segment	Position	Measure debris at
1	0 – 5 m	≥30 cm
2	5 – 10 m	≥0.01 cm
3	10 – 15 m	≥3.0 cm
4	15 – 20 m	≥7.0 cm
5	20 – 25 m	≥7.0 cm
6	25 – 30 m	≥3.0 cm
7	30 – 35 m	≥0.01 cm
8	35 – 40 m	≥30 cm

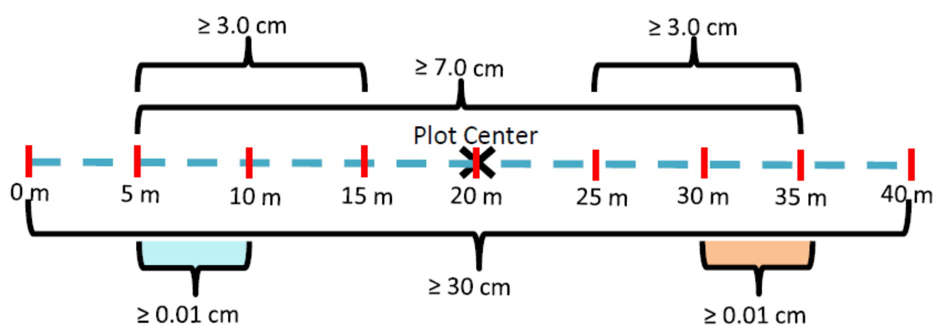
Adapted from Fieldcards (Boucher *et al.*, 2024).

Table 2.5 DWD decomposition stages defined

Stage	Definition
1	Intact, hard.
2	Intact, hard to partly decaying.
3	Hard, large pieces, partly decaying.
4	Small, blocky pieces.
5	Many small pieces, soft portions.

Adapted from Canadian Council of Forest Ministers (2008).

Figure 2.3 Diagram of DWD transects measurements



As shown in Figure 2 (Boucher *et al.*, 2024, p. 8).

To measure tree regeneration, four 1 m^2 microplots were placed along the DWD transects at 10 m from plot centre (Boucher *et al.*, 2024, as cited in Chavardès *et al.*, 2025). All saplings within each microplot were tallied and their species identified. Regeneration classes were assigned to all seedlings based on their height (class 1 = 0 to 14 cm, class 2 = 15 to 59.9 cm, and class 3 = 60 cm to 1.29 m) (see Table 2.6).

Table 2.6 Sapling height classes

Class	**Height Range**
1	0 cm to 14.9 cm
2	15 cm to 59.9 cm
3	60 cm to 1.29 m

2.3. Lab Methods

2.3.1. Data Analysis

Study parameters included species, count, status (live or snag), DBH (cm), BA (m^2/ha), live and dead crown base heights (LCBH and DCBH), percent cover of surface fuels, species, DBH (cm), and count of coarse DWD, count of fine and small DWD, and sapling counts per species and regeneration class (Table 2.7). Statistical analysis was performed on these variables in Excel and RStudio, based on the initial hypotheses stated in Chapter 1:

1. For research objective #1, the null hypothesis (H_0) and the alternative hypothesis (H_1) being tested through statistical analysis are:

   H_0: Forest structure is not different between central and southern plots.

   H_A: Forest structure is different between central and southern plots.

2. For research objective #2, the null and alternative hypotheses are:

   H_0: Regeneration is not different between central and southern plots.

   H_A: Regeneration is different between central and southern plots.

If plots exhibited a similar data distribution between Treatment A and B, they were combined and referred to as 'Southern plots', whereas Control plots were referred to as 'Central plots'.

Table 2.7 Description of study parameters

	Description
Live trees	Trees that were visually classified as live were counted to determine the number of live stems/ha, and their species were identified (Boucher *et al.*, 2024).
Snags	Trees that were dead or dying but still standing and not classified under the red or grey stage were classified as snags, or 'other', and counted to determine the number of snag stems/ha, and their species were identified (Boucher *et al.*, 2024).
DBH (cm)	The diameter at breast height (DBH, cm) of each tree was measured at 1.3 m and was useful for determining the horizontal diversity of each stand (Boucher *et al.*, 2024). Trees were grouped into DBH classes based on 5 cm intervals.
BA (m^2/ha)	DBH values were used to calculate the basal area (BA, m^2/ha) of each stand, representing how much of the horizontal space was taken up by tree trunks (Larsen, 1999).
QMD (cm)	The Quadratic Mean Diameter (cm) of each stand, or the average tree trunk size (Larsen, 2012).
Tree height (m)	The top height (m) was measured for all trees to ensure height measurements for all stand layers (adapted from Boucher *et al.*, 2024).
LCBH and DCBH (m)	The live (LCBH) and dead (DCBH) crown base heights (m) for all coniferous stems with DBH ≥ 9.0 cm were measured. The LCBH was measured at the height of the first whorl (at the base of the stem) where three-quarters of the branches have needles (red or green) and the DCBH was measured at the height of the first whorl (at the base of the stem, except where the dead branches touch the ground) where three-quarters the branches are dead but still baring twigs (Boucher *et al.*, 2024).
Surface cover (%)	The percent cover was estimated by genus for all surface fuel categories (shrubs shorter than 1.30 m, herbs, bryoids, leaves litter, needles litter, and general litter) (Boucher *et al.*, 2024).
Coarse DWD	The species of coarse downed woody debris (DWD), which are fallen trees with a diameter ≥7.0 cm, was identified and its position, tilt angle, and level of decomposition was recorded. Decomposition stages 1 through 5 were assigned to each piece of coarse DWD, offering a rough estimate of the time since the tree fell (Boucher *et al.*, 2024).
Small and fine DWD	Fine and fine downed woody debris (DWD), which are wood fragments and fallen trees with a diameter ≤1.00 cm and ≤3.00 cm respectively, were tallied along specific DWD transect segments (Boucher *et al.*, 2024).
Saplings	The number of saplings was counted by species and height class within each regeneration microplot. Regeneration classes 1 through 3 were assigned to saplings based on their height (cm or m) (Boucher *et al.*, 2024).

Because there are a number of variables in this dataset, a multivariate analysis was performed to offer an interpretation of the complex relationships between structural and regeneration related variables (Chiavetta *et al.*, 2014). First, the Mann-Whitney U test, also called the Wilcoxon Rank Sum test, was used to analyze the statistical significance between plots for variables including live tree and snag density (stems/ha), BA (m^2/ha), QMD (cm), tree height (m), LCR (%), surface cover (%), coarse DWD volume (m^3/ha), and sapling density (stems/ha). Then, the Bray-Curtis test was used to test the level of dissimilarity between plots for the same variables, followed by the Permutational Multivariate Analysis of Variance (PERMANOVA) model to test for statistically significant differences between treatment conditions (Table 2.8).

Table 2.8 Purpose and assumptions of selected non-parametric statistical tests

	Purpose	**Assumptions**
Bray-Curtis Dissimilarity	Measure distance between 0 (samples are identical) and 1 (samples are completely different) (Bray & Curtis, 1957).	Plot area is the same between plots.
Mann-Whitney U Test	Compare the relationship of two independent groups (McClenaghan, 2024).	Independent groups of univariate data that are not normally distributed.
PERMANOVA	Analyze differences in variance between versus within multiple groups (Bakker, 2024).	Independent groups of multivariate, non-parametric data with meaningful distances.

2.3.2. Formulas

Live and dead tree density and snag density (stems/ha) were calculate using the following formula:

$$stems/ha = \frac{\#\ of\ Trees\ in\ Plot}{Plot\ Area\ (ha)}$$

Where:

stems/ha = Stems per hectare.

BA (m^2) was calculated using the following formula (Larsen, 1999):

$$BA = \left(\frac{\pi}{4 * 1000}\right) * DBH^2$$

$$BA = 0.00007854 * DBH^2$$

Where:

BA = Basal area per tree (m^2).

DBH = Diameter at breast height (cm).

Then, BA/ha (m^2) was calculated using the following formula (Larsen, 1999):

$$BA/ha = Tree\ BA * Expansion\ Factor$$

Where:

Expansion Factor = Plot size denominator (e.g., plot size = 0.04 or 1/25th ha, ∴ Expansion Factor = 25)

QMD (cm) was calculated using the following formula (Larsen, 2012):

$$QMD = \sqrt{\frac{BA/tpha}{k}}$$

Where:

QMD = Quadratic mean diameter (cm).

k = Constant (0.00007854).

tpha = Number of trees per hectare.

LCR (%) was calculated using the following formula (Kraft, 1884, as cited by Daniel *et al.*, 1979, as cited in Dean *et al.*, 2009):

$$LCR = \left(\frac{Live\ Crown\ Height}{Total\ Tree\ Height}\right) * \ 100$$

Where:

LCR = Live crown ratio (%).

The volume of DWD was calculated using the following formula (Marshall *et al.*, 2000, as cited in Bawtenheimer-Goncz et al, n.d.):

$$V = \pi^2 \left[\left(\frac{Diameter\ Class\ at\ Intersection^2}{8 * \ Transect\ Length\ (cm)}\right)(\#\ of\ Tallies\ per\ Diameter\ Class)\right]$$

Where:

V = Volume of log (m^3).

Diameter Class at Intersection = Diameter of class of log where intersected along transect (cm).

Importance value (IV %) was calculated for each tree species in the canopy based on the following formulas, which include relative density (%), relative frequency (%), and relative dominance (%):

$$RD = \frac{\#\ of\ Trees\ (Single\ Species)}{Total\ \#\ of\ Trees} * 100$$

$$RF = \frac{\#\ of\ Plots\ \ Containing\ Species}{Total\ \#\ of\ Plots} * 100$$

$$RDom = \frac{Species\ BA}{Total\ BA} * 100$$

$$IV = \ RD + RF + RDominance$$

Where:

RD = Relative density (%).

RF = Relative frequency (%).

RDom = Relative dominance (%).

IV = Importance value (%).

Shannon diversity index was calculated using the following formula (Shannon, 1948; Travis & Larsen, 1995):

$$H = \ -\sum_{i=1}^{c} pilnpi$$

Where:

H = Information content of sample, Index of species diversity, or *Degree of Uncertainty*.

c = Number of species.

pilnpi = Proportion of total sample belonging to i^{th} (species).

CHAPTER 3

Results

3.2. Canopy & Subcanopy Structure

3.2.1. Overview of Site Composition

Across the 15 plots sampled, 458 large trees and 41 small trees were counted, with a total of 8 unique species (Table 3.1, Figure 3.1). Species composition was dominated by eastern hemlock, followed by red spruce. Other species included red maple, yellow birch, Eastern white pine, balsam fir (*Abies balsamea*), white birch, and white ash.

Table 3.1 Species composition and number of trees for each treatment condition

	Species	n large	n small	Total BA (m^2/ha)
Control	Eastern hemlock	101	3	192.95
	Red spruce	37	6	39.72
	Yellow birch	12	-	9.24
	Red maple	9	-	9.62
	White birch	6	-	2.22
	Balsam Fir	2	-	2.02
	Total	**167**	**9**	**255.79**
Treatment A	Eastern hemlock	64	5	187.63
	Red spruce	42	19	43.19
	Red maple	18	-	14.41
	Eastern white pine	4	-	6.32
	Yellow birch	4	-	0.60
	Balsam Fir	1	-	10.87
	White ash	1	-	0.23
	Total	**134**	**24**	**263.26**
Treatment B	Eastern hemlock	114	1	35.38
	Red spruce	22	3	37.33
	Red maple	10	-	210.17
	Eastern white pine	9	-	17.98
	Balsam Fir	-	4	5.72
	Yellow birch	2	-	0.10
	Total	**157**	**8**	**306.69**

Figure 3.1 Canopy and subcanopy live tree and snag count by species for each treatment condition

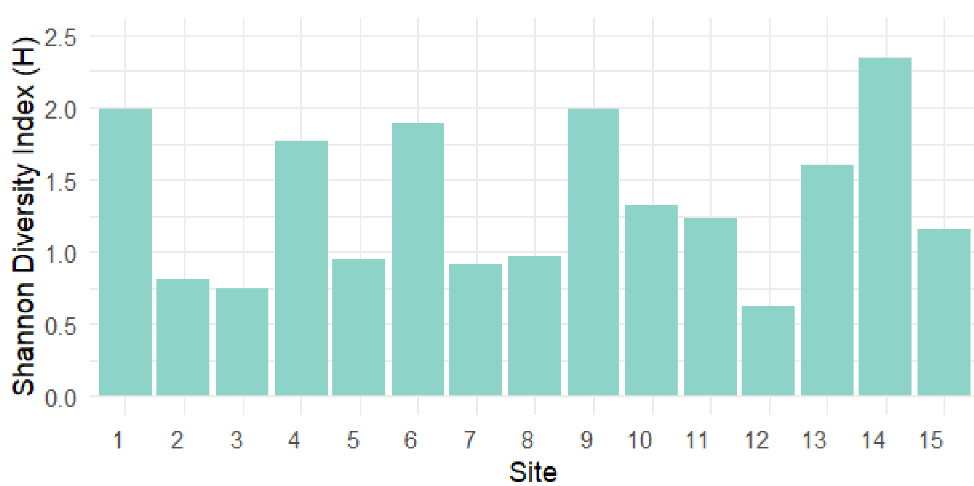
The Shannon Diversity Index (H) was calculated individually for each site for all canopy and subcanopy trees, then the mean, SD, and SE were calculated for each treatment condition (Table 3.2, Figure 3.2). Results indicate a relatively similar mean diversity across the control and treatment plots, with Treatment A showing slightly higher diversity compared to Treatment B; although, significant differences were observed between plots. A relatively high diversity was observed within six of the plots ($1.5 \leq H \leq 3.5$), while a relatively low diversity ($H < 1.5$) was observed within the remaining 9 plots. A low diversity value indicates that plots are dominant by fewer species (Shannon, 1948).

Table 3.2 Summary statistics for Shannon Diversity Index (H) for each treatment condition

	Mean	SD	SE (n = 5*)
Control	1.35	0.55	0.04
Treatment A	1.38	0.44	0.04
Treatment B	1.26	0.47	0.04
Treatment A + B	1.32	0.46	0.03

*For Treatment A + B, SE (n = 10).

Figure 3.2 Shannon Diversity Index (H) for canopy and subcanopy species within each site

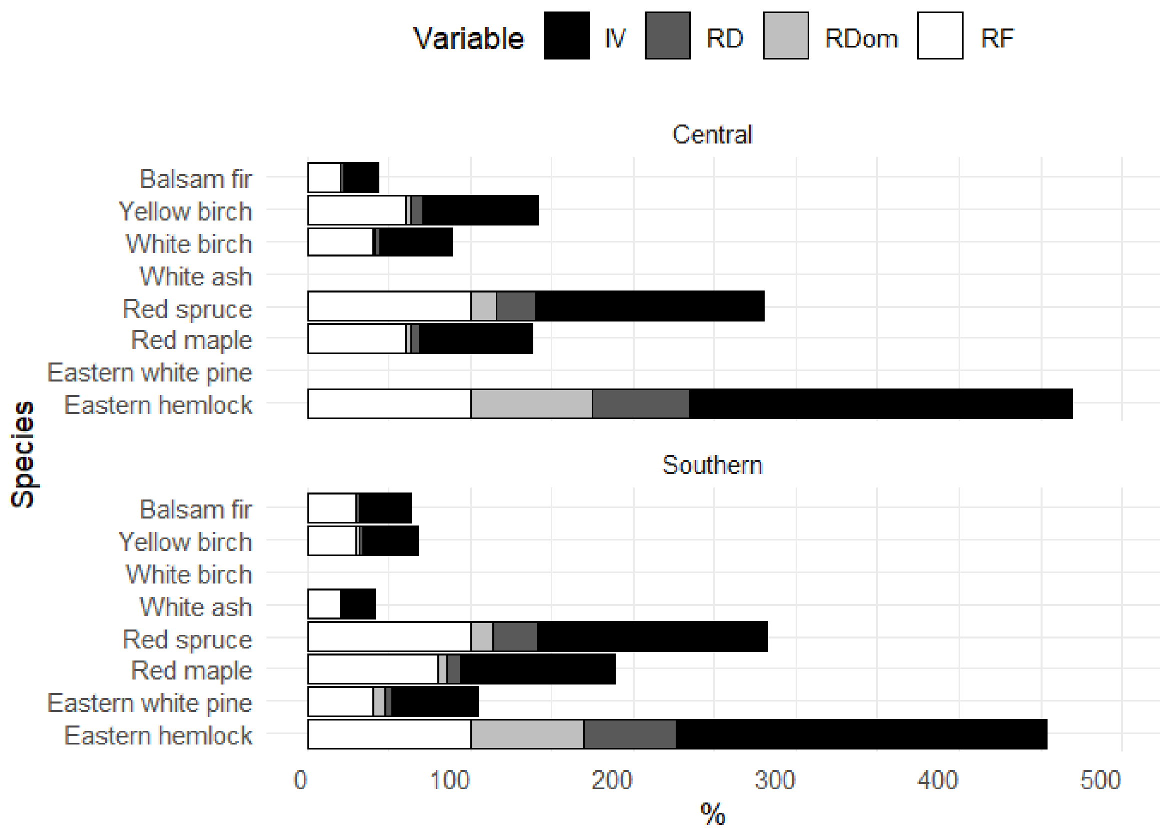


Relative density (RD (%)), relative frequency (RF (%)), relative dominance (RDom (%)), and importance values (IV (%)) were measured for each canopy and subcanopy tree species (Table 3.3). The distributions of these values for the each treatment type are represented in Figure 3.3. Across the five control plots, eastern hemlock dominated all four measurements, followed by red spruce. Across the five Treatment A plots, eastern hemlock dominated all four measurements, followed by red spruce. Across the five Treatment B plots, eastern hemlock dominated all four measurements.

Table 3.3 Relative density, relative frequency, relative dominance, and importance value (%) for canopy and subcanopy species

	n large	**n small**	**Total BA (m^2/ha)**	**RD (%)**	**RF (%)**	**RDom (%)**	**IV (%)**
Control							
Eastern hemlock	101	3	150.97	59.09	100	75.44	234.53
Red spruce	37	6	91.90	24.43	100	15.53	139.96
Yellow birch	12	-	2.63	6.82	60	3.61	70.43
Red maple	9	-	19.11	5.11	60	3.76	68.88
White birch	6	-	4.41	3.41	40	0.87	44.28
Balsam Fir	2	-	6.05	1.14	20	0.79	21.93
Treatment A							
Eastern hemlock	64	5	129.48	43.67	100	71.27	214.94
Red spruce	42	19	157.97	38.61	100	16.41	155.02
Red maple	18	-	27.19	11.39	100	5.48	116.87
Eastern white pine	4	-	9.27	2.53	40	4.13	46.66
Yellow birch	4	-	10.19	2.53	40	2.40	44.93
Balsam Fir	1	-	2.53	0.63	20	0.09	20.72
White ash	1	-	0.81	0.63	20	0.23	20.86
Treatment B							
Eastern hemlock	114	1	215.25	69.70	100	68.53	238.23
Red spruce	22	-	32.31	15.15	100	11.54	126.69
Red maple	10	-	21.05	6.06	60	5.86	71.92
Eastern white pine	9	-	24.85	5.45	40	12.17	57.63
Yellow birch	2	-	3.85	1.21	20	1.86	23.08
Balsam Fir	-	4	12.67	2.42	40	0.03	42.46

Figure 3.3 Relative density, relative frequency, relative dominance, and importance value (%) for canopy and subcanopy species in Central and Southern plots



3.2.2. Overview of tree density

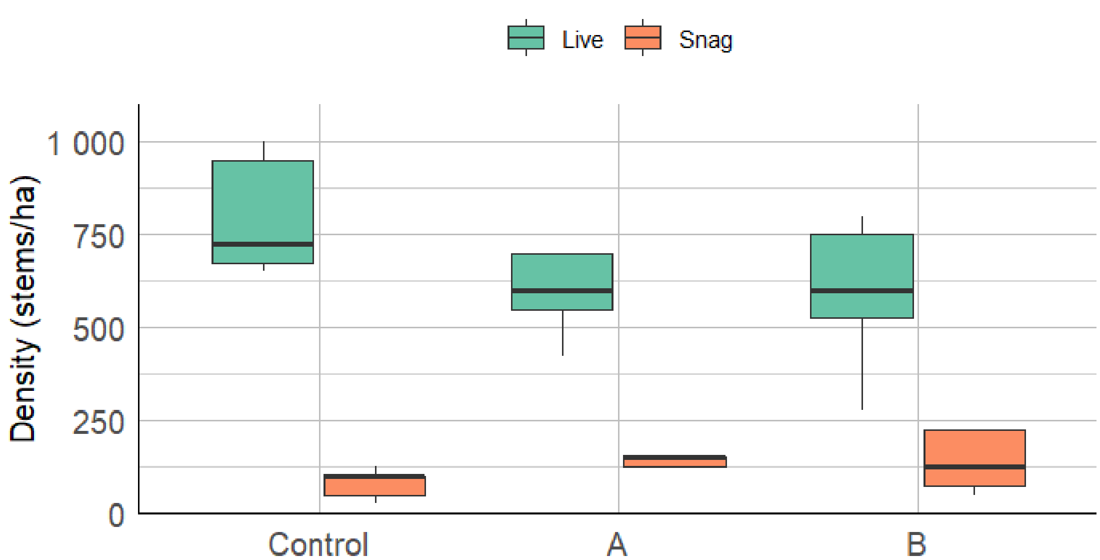
The mean tree density (stems/ha) was calculated for each treatment condition, including SD and SE (Table 3.4). Canopy trees (height ≥ 1.3 m and DBH ≥ 9 cm) and subcanopy trees (height ≥ 1.3 m and DBH < 9 cm) were treated separately. Trees were also treated separately based on status (live, dead, or other). Results indicate discrepancies between treatment types, and reveal a significantly higher proportion of snags in Southern plots as compared to Central rplots.

Table 3.4 Stand summary statistics for tree density (stems/ha)

	Canopy			Subcanopy		
	Mean	**SD**	**SE (n = 5*)**	**Mean**	**SD**	**SE (n = 5*)**
Control						
Live tree density (stems/ha)	770	1.40	0.63	30	0.37	0.17
Snag density (stems/ha)	65	0.50	0.22	15	0.50	0.22
Treatment A						
Live tree density (stems/ha)	995	2.29	1.02	170	0.77	0.34
Snag density (stems/ha)	235	11.50	5.14	45	4.50	2.01
Treatment B						
Live tree density (stems/ha)	585	1.88	0.84	40	1.00	0.45
Snag density (stems/ha)	200	3.00	1.34	-	-	-
Treatment A + B						
Live tree density (stems/ha)	790	2.15	0.68	105	24.93	7.88
Snag density (stems/ha)	217.5	8.58	2.71	22.5	3.90	1.23

*For Treatment A + B, SE (n = 10).

Figure 3.4 Distribution of density for live trees and snags (stems/ha) by treatment type



3.2.3. Overview of Tree Size

Tree height (m), DBH (cm), and LCR (%) were included size measurements for canopy and subcanopy trees. For each treatment condition, the mean, standard deviation, and standard error was calculated for each tree size variable. Trees were also treated separately based on status (live or snag). The distribution of BA (m^2/ha) was calculated based on 5 cm DBH classes to compare plot structure between treatment types, as represented in Figure 3.5. Central plots had an uneven distribution, with a maximum DBH range of 65 to 70 cm, and the most frequent being from 20 to 25 cm. Southern plots also had an uneven distribution, skewing heavily to the right with significantly more observations in DBH classes above 50 cm than in Central plots. For both regions, eastern hemlock dominated nearly all DBH classes, except for the 20 to 25 cm class in Central plots and the 0 to 5 cm and 10 to 15 cm classes in the Southern plots, which were dominated by balsam fir.

Figure 3.5 Distribution of BA (m²/ha) by DBH class (cm) for live tree species by treatment type

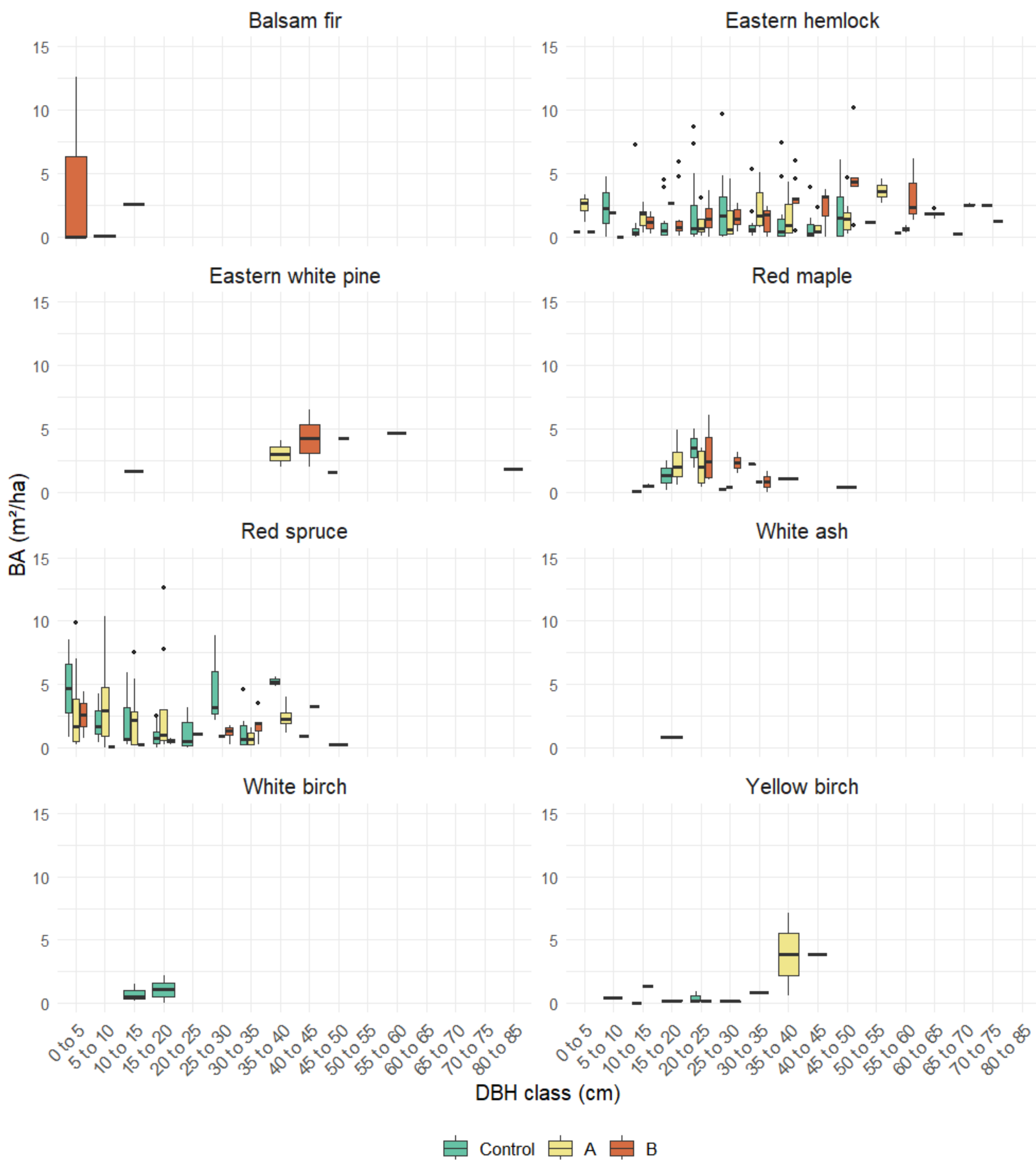


Figure 3.6 Distribution of live tree count, BA (m²/ha), and height (m) per DBH class (cm) in Central and Southern plots

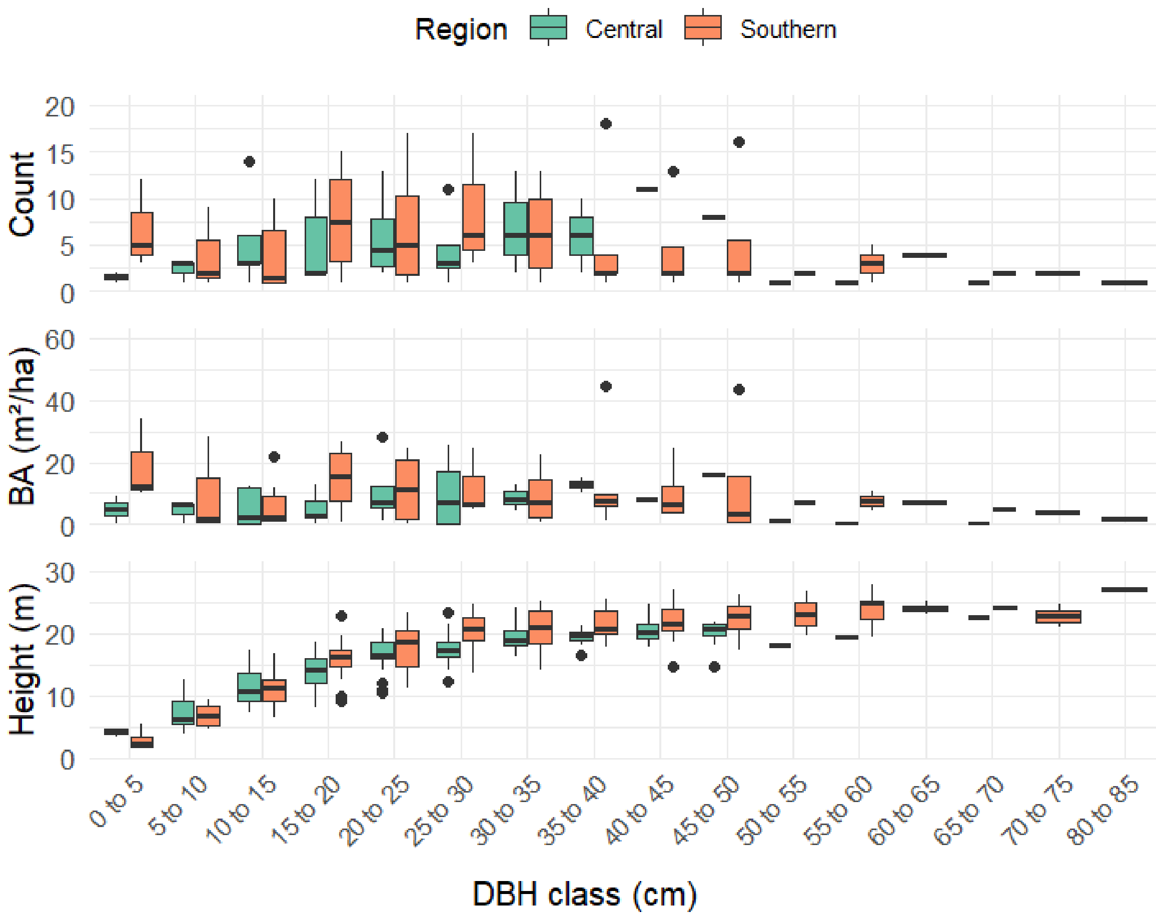
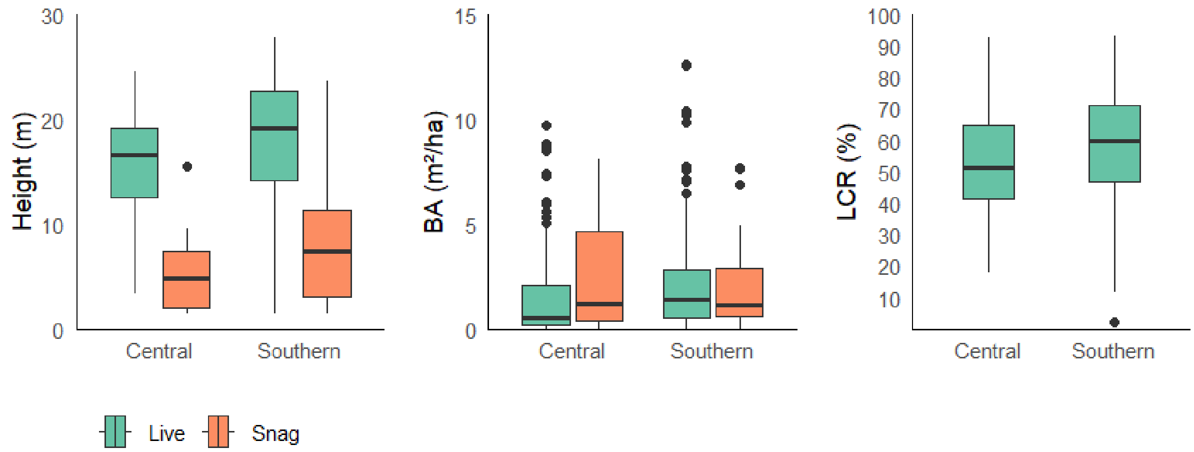


Table 3.5 Stand summary statistics for size related variables

	Canopy			Subcanopy		
	Mean	**SD**	**SE (n = 5*)**	**Mean**	**SD**	**SE (n = 5*)**
Control						
BA for live trees (m^2/ha)	1.58	1.40	0.63	0.04	0.01	0.01
BA for snags (m^2/ha)	1.73	0.19	0.08	0.03	0.02	0.01
Live tree QMD (cm)	29.26	11.53	0.96	-	-	-
Snag QMD (cm)	28.53	12.16	8.60	1.00	-	-
Live tree height (m)	16.30	4.16	1.86	4.52	0.94	0.42
Snag height (m)	6.26	2.46	1.10	2.63	1.03	0.46
LCR (%)	51.46	22.98	10.28	37.23	18.21	8.14
Treatment A						
BA for live trees (m^2/ha)	2.50	2.29	1.02	0.03	0.03	0.01
BA for snags (m^2/ha)	1.46	0.03	0.01	0.03	0.02	0.01
Live tree QMD (cm)	35.28	15.31	1.49	0.95	0.24	0.12
Snag QMD (cm)	21.03	7.45	2.36	0.60	-	-
Live tree height (m)	18.05	5.22	2.34	3.10	1.58	0.71
Snag height (m)	8.71	2.63	1.17	1.73	1.73	0.77
LCR (%)	57.84	17.33	7.75	54.88	13.03	5.83
Treatment B						
BA for live trees (m^2/ha)	2.23	1.88	0.84	0.03	0.04	0.02
BA for snags (m^2/ha)	2.27	0.07	0.03	-	-	-
Live tree QMD (cm)	34.13	12.23	1.18	0.81	0.57	0.40
Snag QMD (cm)	25.69	15.18	3.04	-	-	-
Live tree height (m)	20.18	4.28	1.92	2.81	1.31	0.58
Snag height (m)	9.72	3.21	1.44	-	-	-
LCR (%)	54.00	17.29	7.73	61.53	11.40	5.10
Treatment A + B						
BA for live trees (m^2/ha)	2.37	2.15	0.68	0.03	1.95	0.62
BA for snags (m^2/ha)	1.87	0.21	0.07	0.02	0.02	0.01
Live tree QMD (cm)	34.70	13.81	0.95	0.90	0.33	0.14
Snag QMD (cm)	24.45	13.33	2.25	0.60	-	-
Live tree height (m)	19.11	5.00	1.58	2.95	8.35	2.64
Snag height (m)	9.22	2.98	0.94	0.86	1.50	0.47
LCR (%)	55.92	17.38	5.50	58.21	12.88	4.07

*For Treatment A + B, SE (n = 10).

Figure 3.7 Distribution of height (m), BA (m²/ha), and LCR (%) for canopy and subcanopy trees and snags in Central and Southern plots



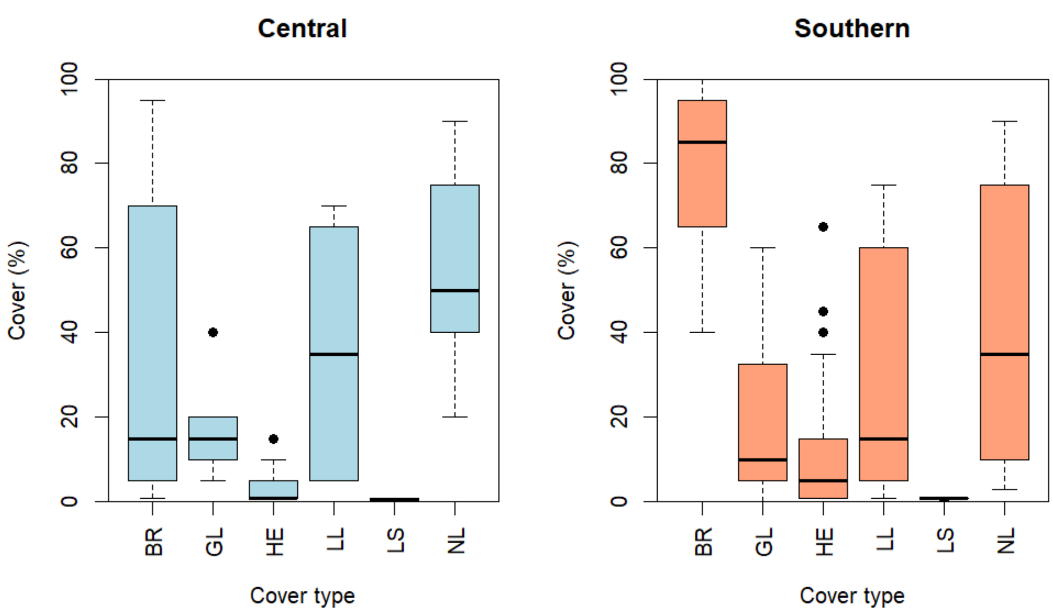
3.2.4. Surface Cover

The mean surface cover (%) was calculated for all surface cover types, and for each type individually within each treatment condition, with SD and SE included (Table 3.6, Figure 3.8). In both Central and the Southern plots, the dominant surface cover type was bryoids (BR), accounting for the highest proportion of total surface cover in both regions Additionally, needle litter (NL) and leaf litter (LL) represented a significant portion of the surface cover in both regions. General litter (GL) and herbs (HE) were relatively low, while low shrubs (LS) were rarely present.

Table 3.6 Summary statistics for surface cover (%)

	Mean	SD	SE (n = 5)
Control			
Cover (%) low shrubs	0.50	0.71	0.32
Cover (%) herbs	3.36	3.82	1.71
Cover (%) bryoids	37.20	42.59	19.05
Cover (%) litter	36.33	28.25	12.63
Treatment A			
Cover (%) low shrubs	1.00	-	-
Cover (%) herbs	4.62	5.07	2.27
Cover (%) bryoids	92.00	7.58	3.39
Cover (%) litter	14.31	14.04	6.28
Treatment B			
Cover (%) low shrubs	0.86	0.38	0.17
Cover (%) herbs	14.17	15.38	6.88
Cover (%) bryoids	66.00	22.19	9.92
Cover (%) litter	43.00	30.58	13.68
Treatment A + B			
Cover (%) low shrubs	0.93	26.98	8.53
Cover (%) herbs	9.40	24.37	7.71
Cover (%) bryoids	79.00	31.70	10.03
Cover (%) litter	35.81	25.31	8.00

Figure 3.8 Cover (%) by surface cover type in Central and Southern plots



3.2.5. DWD Composition and Volume

The distribution of coarse DWD volume was calculated based on 5 cm diameter classes to compare the species composition of coarse DWD between Central and Southern plots, as represented in Figure 3.9. In Central plots, very little eastern hemlock mortality was detected among coarse DWD as compared to Southern plots (Table 3.7, Figure 3.9). This discrepancy is apparent when looking at the volume (m^3/ha) of coarse DWD, which is dominated by eastern hemlock in 54.5% of the diameter classes in Southern plots. Additionally, softwood and eastern hemlock dominated the two largest diameter classes in Southern plots, accounting for more than 30 m^3/ha. Large counts of softwood and unknown coarse DWD species were detected in both the Central and Southern plots, which contributed significantly to the volume of coarse DWD found in Southern plots. Notably, red spruce was the second most dominant coarse DWD species based on count and volume for both regions. Other species included red maple, trembling aspen (*Populus tremuloides*), yellow birch, white birch, and a small amount of hardwood and eastern white pine. No balsam fir or white ash was detected among the coarse DWD at any of the plots. For each treatment condition, the mean, standard deviation, and standard error was calculated for coarse DWD, then, results were grouped to compare Central and Southern plots (Table 3.8, Figure 3.10).

Table 3.7 Coarse DWD species composition, number of trees, and total volume (m³/ha) for each treatment condition

	Species	n	Total Volume (m³/ha)
Control	Red spruce	27	9.26
	Softwood	25	4.94
	Unknown	21	3.52
	White birch	13	7.54
	Eastern hemlock	7	1.50
	Yellow birch	7	0.34
	Red maple	3	4.94
	Hardwood	1	0.10
	Trembling aspen	1	4.23
	Total	**105**	**36.37**
Treatment A	Unknown	36	12.51
	Softwood	32	6.87
	Red spruce	10	5.23
	Eastern hemlock	5	14.57
	Red maple	2	0.95
	Yellow birch	2	4.48
	Total	**87**	**44.61**
Treatment B	Softwood	46	24.54
	Unknown	27	10.84
	Eastern hemlock	20	10.68
	Red spruce	9	13.37
	Red maple	6	3.11
	Eastern white pine	1	0.05
	Total	**109**	**62.60**

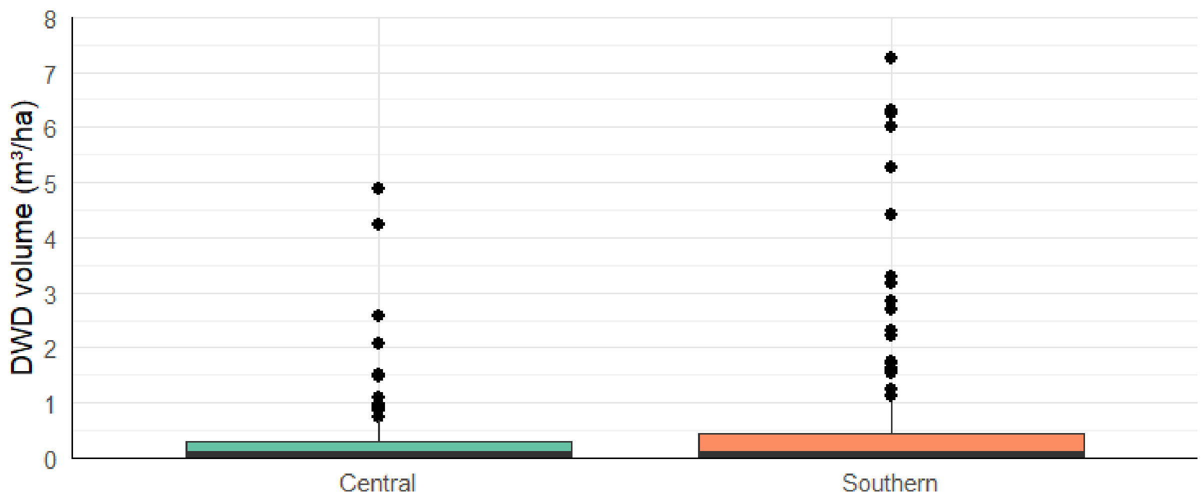
Figure 3.9 Count and volume (m3/ha) of coarse DWD by diameter class (cm) and species in Central and Southern plots

Table 3.8 Summary statistics for coarse DWD volume (m³/ha)

	Mean	SD	SE (n = 5*)
Control	34.64	73.34	32.80
Treatment A	51.28	123.92	55.42
Treatment B	57.43	118.26	52.89
Treatment A + B	54.35	120.53	38.12

*For Treatment A + B, SE (n = 10).

Figure 3.10 Distribution of DWD volume (m3/ha) in Central and Southern plots



3.3. Regeneration Status

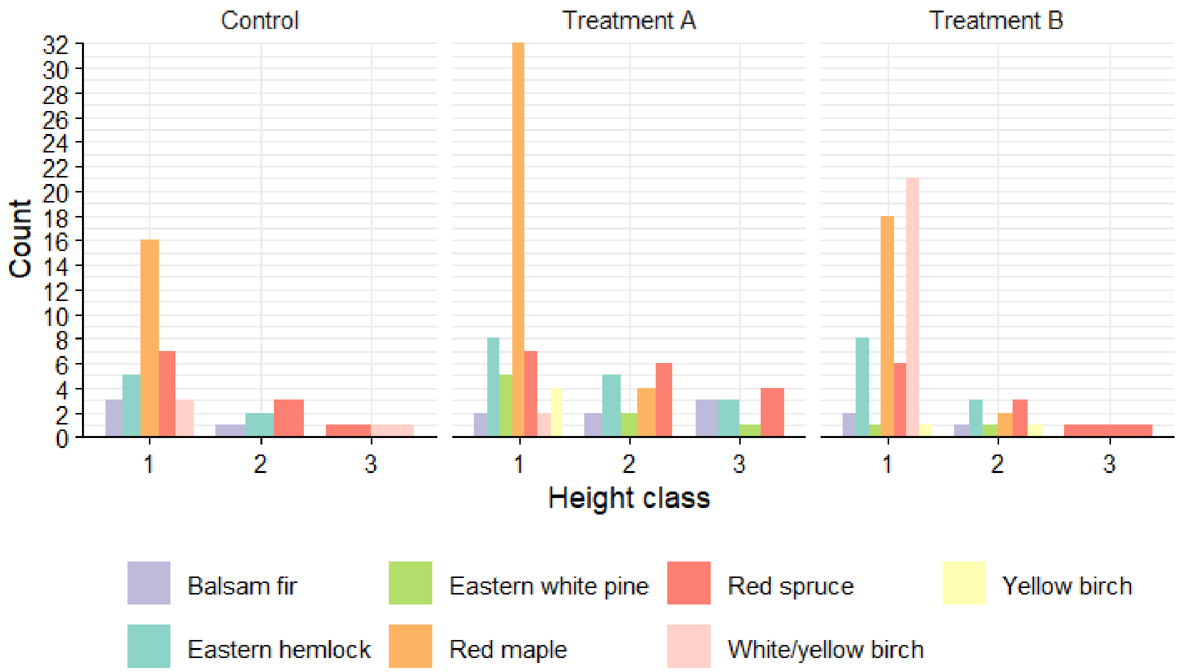
3.3.1 Overview of Composition

Count distributions were calculated for each seedling species, based on the defined height classes each treatment conditions (Table 3.9, Figure 3.11). Across the 15 plots sampled, a total of 191 seedlings were counted, 141 of which were in heigh class 1, 36 were in height class 2, and 14 were in height class 3, with a total of seven unique species. Overall, the dominant regenerating species was red maple, followed by red spruce and eastern hemlock. Other species included balsam fir, white/yellow birch, eastern white pine, and yellow birch. White ash, which had one occurrence in Treatment A's canopy, and trembling aspen, which had one occurrence in Control's coarse DWD, did not appear in the regeneration layer. Notably, very few individuals were detected in height class 3 across all treatment conditions. Further, red maple rarely was counted past height class 1, and did not appear at all in height class 3. Red spruce was the dominant species found in height class 3 with a total of 6 individuals across the three treatment conditions.

Table 3.9 Total number of tree seedlings per species and height class

	Species	Height Class 1	Height Class 2	Height Class 3
Control	Red maple	16	-	-
	Red spruce	7	3	1
	Eastern hemlock	5	2	-
	Balsam Fir	3	1	-
	White/yellow birch	3	-	1
Total		**34**	**6**	**2**
Treatment A	Red maple	32	4	-
	Red spruce	7	6	4
	Eastern hemlock	8	5	3
	Eastern white pine	5	2	1
	Yellow birch	4	-	-
	Balsam Fir	2	2	3
	White/yellow birch	2	-	-
Total		**60**	**19**	**11**
Treatment B	Red maple	18	2	-
	White/yellow birch	11	-	-
	Eastern hemlock	8	3	-
	Red spruce	6	3	1
	Balsam Fir	2	1	-
	Eastern white pine	1	1	-
	Yellow birch	1	1	-
Total		**47**	**11**	**1**

Figure 3.11 Distribution of seedling counts by species and height class for each treatment condition



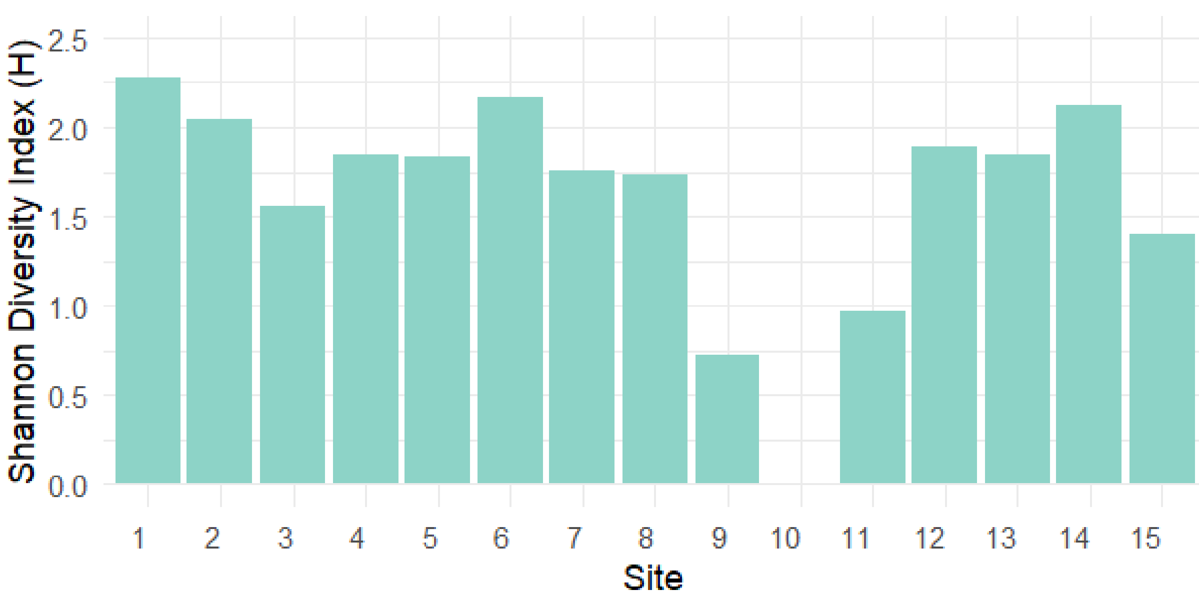
The Shannon Diversity Index (H) value was calculated individually for all seedlings at each site, then the mean, SD, and SE were calculated for each treatment condition (Table 3.10, Figure 3.12). Results indicate a moderate level of diversity in Central plots. In contrast, both Treatment A and Treatment B plots had a lower mean diversity. indicating a decrease in diversity compared to Control plots. When Treatment A and B plots were combined, the mean H increased slightly, though Southern plots still maintained a lower mean diversity than Central plots. No diversity was observed among the seedling regeneration at site 10, as only red spruce was present.

Table 3.10 Summary statistics for Shannon Diversity Index (H) for each treatment condition

	Mean	**SD**	**SE (n = 5*)**
Control	1.55	0.42	0.06
Treatment A	1.06	0.66	0.09
Treatment B	1.06	0.47	0.07
Treatment A + B	1.22	0.48	0.00

*For Treatment A + B, SE (n = 10).

Figure 3.12 Shannon Diversity Index (H) for sapling species at each site



3.3.2 Overview of Sapling Density

Mean sapling density (stems/ha) was calculated for each treatment condition, including SD and SE (Table 3.11, Figure 3.13). The results revealed a significant difference in the distribution of sapling density between the three treatment conditions. To explore this discrepancy further, the distribution of sapling density was calculated individually by species and treatment condition (Figure 3.14). All sapling density results consistently show that red maple is the dominant regenerating species. However, the second and third most dominant species were inconsistent, with possibilities including Eastern hemlock, red spruce and white/yellow birch.

3.11 Summary statistics for regeneration density

	Mean	SD	SE (n = 5*)
Control			
Sapling density (stems/ha) for all	580.00	15.84	7.09
Sapling density (stems/ha) for height class 1	525.00	17.02	7.61
Sapling density (stems/ha) for height class 2	50.00	5.16	2.31
Sapling density (stems/ha) for height class 3	5.00	-	-
Sapling density (stems/ha) for Eastern hemlock	105.00	16.07	7.19
Sapling density (stems/ha) for red spruce	80.00	4.10	1.83
Treatment A			
Sapling density (stems/ha) for all	1325.00	39.30	17.58
Sapling density (stems/ha) for height class 1	1135.00	46.29	20.70
Sapling density (stems/ha) for height class 2	130.00	6.43	2.88
Sapling density (stems/ha) for height class 3	60.00	12.25	5.48
Sapling density (stems/ha) for Eastern hemlock	95.00	14.92	6.67
Sapling density (stems/ha) for red spruce	120.00	15.58	6.97
Treatment B			
Sapling density (stems/ha) for all	2575.00	89.30	39.93
Sapling density (stems/ha) for height class 1	2235.00	93.16	41.66
Sapling density (stems/ha) for height class 2	335.00	77.86	34.82
Sapling density (stems/ha) for height class 3	5.00	-	-
Sapling density (stems/ha) for Eastern hemlock	110.00	8.06	3.61
Sapling density (stems/ha) for red spruce	390.00	80.55	36.02
Treatment A + B			
Sapling density (stems/ha) for all	1950.00	70.25	22.22
Sapling density (stems/ha) for height class 1	1685.00	76.20	24.10
Sapling density (stems/ha) for height class 2	232.50	54.75	17.31
Sapling density (stems/ha) for height class 3	32.50	11.34	3.59
Sapling density (stems/ha) for Eastern hemlock	102.50	10.96	3.46
Sapling density (stems/ha) for red spruce	255.00	60.71	19.20

*For Treatment A + B, SE (n = 10).

Figure 3.13 Density distributions for saplings (stems/ha) in Central and Southern plots

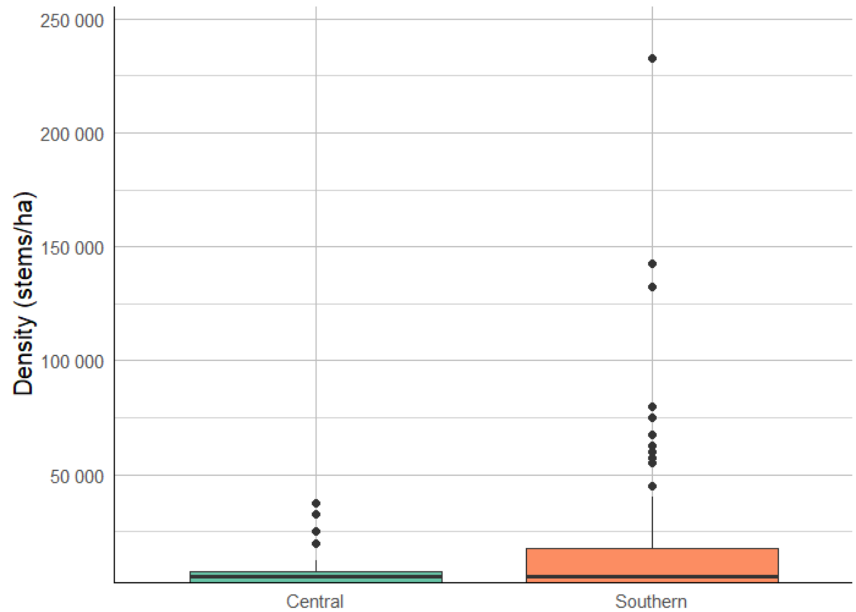
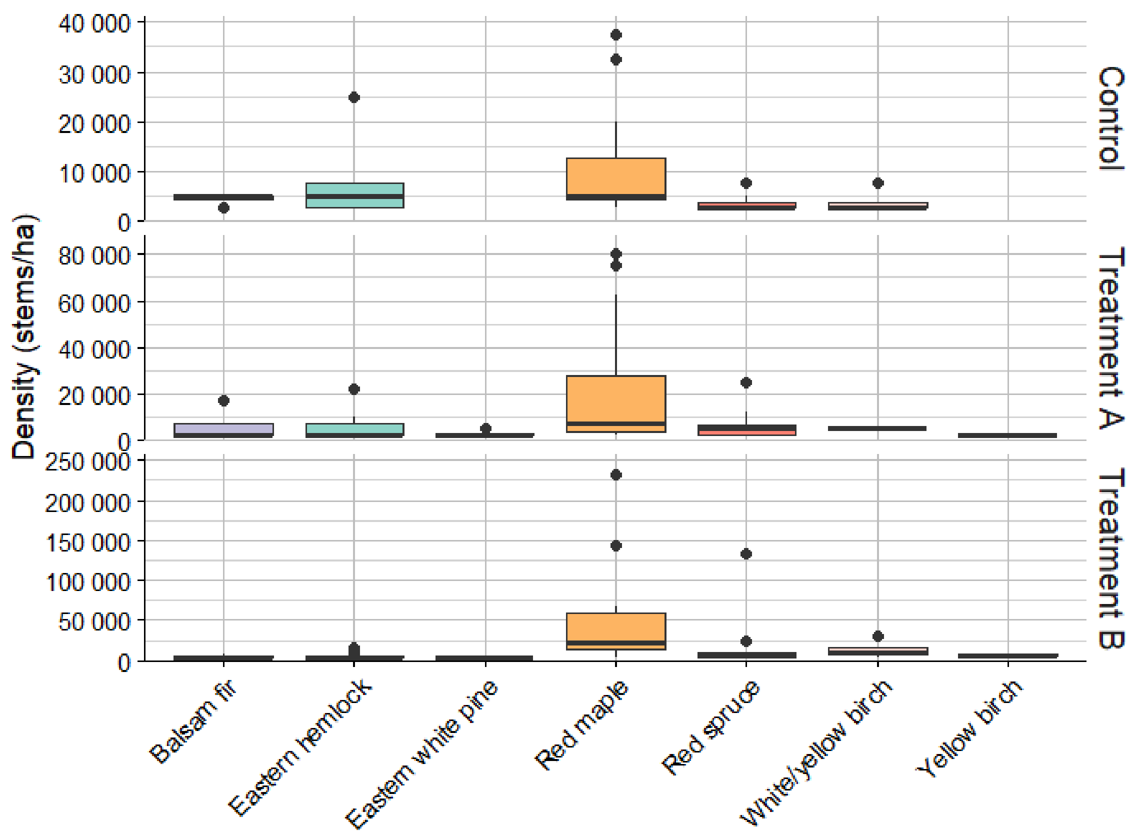


Figure 3.14 Density distributions for saplings (stems/ha) by species and treatment condition



3.3. Statistical Significance

After looking at the initial distribution results, several non-parametric tests were chosen to compare variables of interest between the Central and Southern plots (Table 3.12). Results of the Mann-White U test revealed statistically significant differences in the distributions of mean density of live trees, snags, and saplings (stems/ha), as well as BA (m^2/ha) and top height (m) for canopy and subcanopy trees across the three treatment conditions (Table 3.13). On the other hand, no statistically significant differences were found in the distributions of mean LCR (%), live tree or sapling Shannon Diversity Index (H), mean surface cover (%), or mean DWD volume (m^3/ha).

Table 3.12 Results of Mann-Whitney U test of statistical significance for selected variables

	W Statistic	P Value
Mean live tree density (stems/ha)	2406	< 0.001
Mean snag density (stems/ha)	419	< 0.001
Mean sapling density (stems/ha)	357	< 0.001
Mean BA (m^2/ha)	661	< 0.001
Mean top height (m)	966	0.013
Mean LCR (%)	1148	0.174
Mean surface cover (%)	1279	0.580
Mean DWD volume (m^3/ha)	1172	0.226
Live tree Shannon Diversity Index (H)	1079	0.075
Sapling Shannon Diversity Index (H)	1395	0.878

Results of the Bray-Curtis and PERMANOVA analyses indicated that the differences observed between stand structure and regeneration density in the Central and Southern plots were moderately significant (p = 0.058, Figure 3.15, Figure 3.16). These findings are consistent with the null hypotheses stated in Chapter 2.

Figure 3.15 Bray-Curtis dissimilarity matrix for selected variables

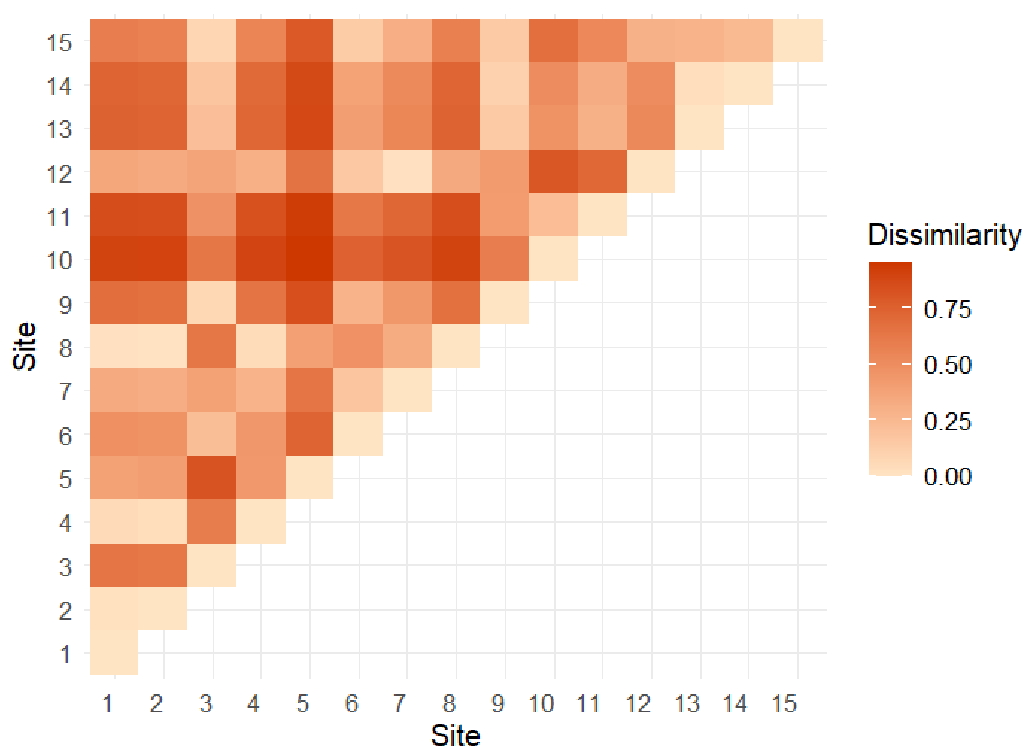
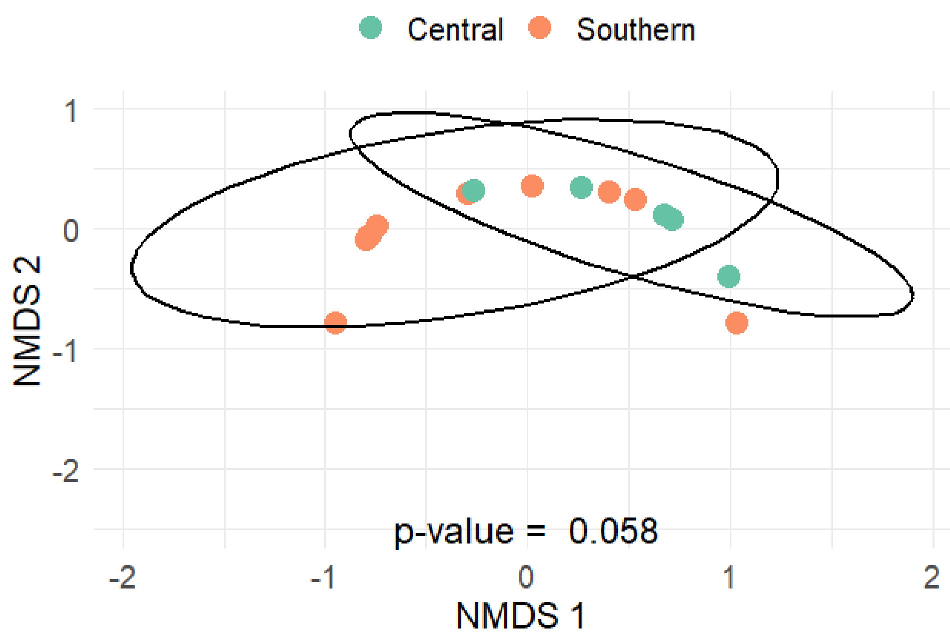


Figure 3.16 PERMANOVA analysis for selected variables



CHAPTER 4

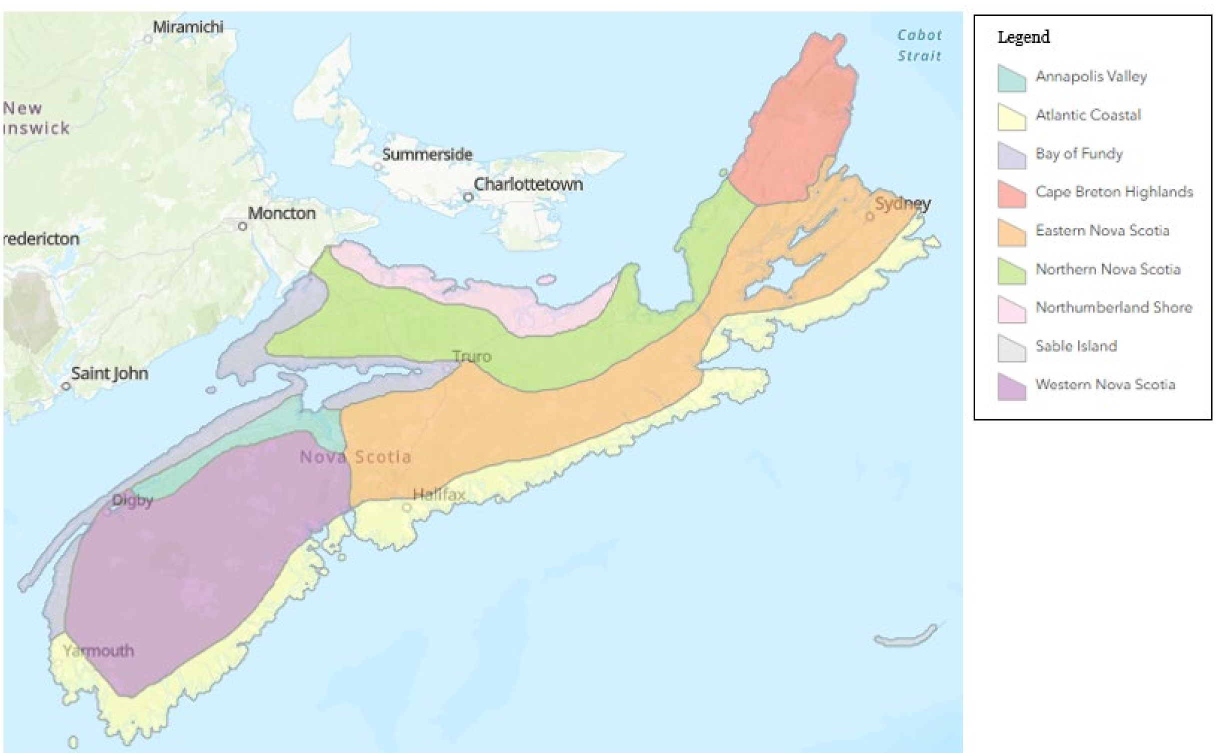
Discussion

4.1. Stand Dynamics & Tree Health

4.1.1. Quantifying Structural Similarities & Differences

Notable differences were detected between the heavily defoliated and moderate to lightly defoliated stands, which is likely attributed to variations between different ecosite conditions. Much of the variation in stand structure and composition between the Southern and Central plots are likely due to more distinguishable regional climate variations and differences in elevation, as the plots are in different ecoregions with unique nutrient and moisture regimes. For example, all Southern plots were located in the Western Nova Scotia climate zone, defined by a gradual slope upwards from the Atlantic Coast, with high rainfall and warmer temperatures than eastern Nova Scotia, whereas Central plots were either in the Eastern Nova Scotia climate zone, defined by a diverse geographic area with high rainfall and generally cool temperatures, influenced by the Nova Scotia Current, or the Northern Nova Scotia climate zone, defined by highlands which receive high snowfall and have the coldest winter temperatures, but quite warm summer temperatures (Figure 4.1; Nova Scotia Museum of Natural History, 2013). Additionally, because HWA has been migrating from its southwestern most origin in the province, the pest has had more time to establish its presence in those plots. Plots in the Central region of the province which have not yet been affected by HWA had the highest diversity and live tree density (stems/ha), and the lowest snag density (stems/ha), DWD volume (m^3/ha). No statistically significant differences were found in the distribution of mean LCR (%), live tree or sapling Shannon Diversity Index (H), mean surface cover (%), or mean DWD volume (m^3/ha) across the three treatment conditions, suggesting that none of these variables were attributed to the presence of HWA, whereas a distinct relationship was found among the distribution of mean density of live trees, snags, and saplings (stems/ha), as well as mean BA (m^2/ha) and top height (m) for canopy and subcanopy trees. Interestingly, no red oak was detected within any of the plots (although it was detected at some plots), despite its high frequency throughout the southwestern part of the province (Butt *et al.*, 2023).

Figure 4.1 Map of Nova Scotia's climate zones



Adapted from NSAtlasDev, 2017.

4.1.2. Evidence of Eastern Hemlock Decline

Evidently, there is a statistically significant difference between plots in the Southern region of Nova Scotia which have been impacted by HWA and those in the Central region where the pest has yet to spread. However, it is important to consider the influence that the different sample sizes could have on these results, with twice as many plots in the Southern region than in the Central region. This could suggest that data collected from Central plots is less reliable and more likely to be a result of random variation. Regardless, eastern hemlock mortality is undoubtedly taking place in Southwestern Nova Scotia, although it is difficult to understand the rate at which this is occurring with the limitation of a smaller sample size among the control plots.

Already, a significant amount of hemlock mortality has been detected through this study, especially when looking at the difference in mean snag count and coarse DWD volume (m^3/ha) between the three treatment conditions. Although, these attributes are not exclusively associated with HWA presence, and could be a result of wind storms, hurricanes, or other natural disturbances. However, if this were the case, there would likely be more variation in the species composition of snags and DWD. Eastern hemlock was found to be dying at the fastest rate in heavily defoliated plots (Treatment B). In comparison, plots that were not impacted by HWA had a greater frequency of eastern hemlock among live tree counts, had very few snags, and had a much smaller DWD volume (m^3/ha). Despite the significant presence of eastern hemlock mortality in Southern plots, the species remained well established as the most important species across the treatment conditions, and was found to have the highest importance in the heavily defoliated plots based on IV (%).

Based on past trends throughout New England, significant hemlock mortality is followed by a rapid change in forest cover (Ellison *et al.*, 2018). In the wake of a changing climate, HWA is expected to migrate further north in the province, and it is becoming most resistant to harsh winter temperatures. Not only will climate change affect the spread of HWA, but the pest may also affect the severity of climate change in the province. For example, with enough eastern hemlock mortality, especially in stands where it is the dominant species, a noticeable reduction will occur in the overstory, which acts a form of shade control for understory vegetation and other forms of life. A significant loss in canopy cover will result in a reduced cooling effect on the forest floor, which could potentially impact nearby environments and waterways (Paradis *et al.*, 2008, Siderhurst *et al.*, 2010, McAvoy *et al.*, 2017). Due to the complex relationship between overstory and understory composition and diversity, vegetation on the forest floor will likely face the most significant changes in heavily defoliated plots.

Eastern hemlock contributes to its environment in various ways, by controlling light availability, insulation, and evapotranspiration rates through the canopy, and reducing soil pH through the decomposition of needle litter (Lustenhouwer *et al.* 2012; Orwig *et al.* 2008, as cited in Cox *et al.*, 2022). Research from Zangy *et al.* (2021) looked at environmental filtering, resource heterogeneity, and resource density as driving factors of diversity among plant communities, and found that environmental filtering was the primary driver of understory diversity. This suggests that the reduced canopy cover resulting from a significant loss of eastern hemlock would likely increase species diversity on the forest floor. Bryoids and mosses, which were the most dominant surface cover type in Southern plots, are shade-tolerant species requiring a high-moisture environment (Marschall & Proctor, 2004). The drier conditions from a loss in canopy cover in a heavily defoliated scenario would likely result in a loss of surface cover, which could potentially degrade the underlying soils and produce a less nutrient rich environment. Therefore, surface cover will likely be replaced by early successional, shade-intolerant species that are highly resource-efficient, able to thrive in nutrient-poor environments.

As a keystone species, eastern hemlock shares a complex co-existing relationship with various other species, which changes based on the forest type of a given stand, defined by moisture and nutrient regimes (Neily *et al.*, 2023). Throughout New England, rhododendron (*Rhododendron maximum*) can be found as a co-occurring, shade-tolerant canopy species alongside eastern hemlock, contributing to the shrub layer but reducing the ability for seedling regeneration (Ford *et al.*, 2011). Further, eastern hemlock is known to be associated with at least 75 species of ectomycorrhizal fungi in temperate forests, acting as the host for an extremely diverse fungal community (Baird *et al.*, 2014, as cited in Caruso *et al.*, 2021). Eastern hemlock mortality has been shown to reduce ectomycorrhizal fungi colonies by up to 67%, largely due to a reduced photosynthetic capacity in trees infested with HWA and lower carbon allocation below the forest floor (Vendettuoli *et al.,* 2015, as cited in Caruso *et al.*, 2021). Fungal communities are quite resilient and are expected to find new hosts in the aftermath of HWA-induced mortality, although, they will face significant losses in diversity (Mader *et al.*, 2023).

4.1.2. Beginnings of Post-Disturbance Successional Pathways

Ultimately, the regenerating structure is expected to change most significantly in stands with the largest canopy openings, which are likely those with the most severe eastern hemlock defoliation. Increased light availability for understory vegetation will reduce the amount of competition over community resources and therefore increase species richness (Dormann *et al.*, 2020). Although red maple was the most frequent regenerating species, results showed that it was not present in height class 3 at any of the plots, and it was not very well established as a canopy or subcanopy tree either. This could indicate that red maple has only recently began regenerating, as it only grows at a rate of 0.3 m in the first year and 0.6 m each year for the next few years (Walters & Yawney, n.d.). Eastern hemlock and red spruce were equally the second most dominant when looking at the total seedling count per species, however, their distributions varied between plots. Overall, the high seedling density (stems/ha) suggests that plots impacted by HWA are already regenerating, and that species composition is relatively similar to the structure of the canopy. In New England, black birch (*Betula lenta*) was found to dominate the forest community immediately following eastern hemlock mortality (Orwig and Foster 1998, Cobb 2010, as cited in Ford *et al.*, 2011). Further, post-HWA succession in New England's southern Appalachian forests is expected to either be dominated by rhododendron, if they are able to overtake the surface layer, or by co-occurring hardwood species that can outcompete other regenerating species (Ford and Vose 2007, Kincaid and Parker 2008, Roberts *et al.* 2009, as cited in Ford *et al.*, 2011). In the event of significant canopy loss due to HWA infestations, shade-intolerant hardwood species such as red maple, white birch, grey birch (*Betula populifolia*), trembling aspen, large-tooth aspen (*Populus grandidentata*), red oak and white ash will likely have increased chances of regenerating (Government of Nova Scotia, n.d.). Therefore, red maple is expected to be the most successful regenerating species in heavily defoliated stands eastern hemlock stands in Nova Scotia, however, species composition will ultimately depend upon the forest type and climatic conditions.

CHAPTER 5

Conclusion

5.1. Recommendations & Further Research Requirements

This research provided insight into the severity of stand-level defoliation among eastern hemlock in Nova Scotia, although, more research is required to understand the long-term impacts. The data from this study could be useful for making prediction and modeling scenarios for regeneration. It is essential that monitoring is conducted on a regular basis to track the progress of its distribution for its effective management. Degrassi *et al.* (2019) argue that even the most common species need to be conserved, especially foundational species such as eastern hemlock. Without past stand level data to compare this research to, it is challenging to track the impact HWA has over time. Future research should focus on making observations within the same plots over a number of years to fully capture changes to stand dynamics over time, and should aim to include variables such as age and time, for example, by cross-dating live tree species with snags and DWD to better understand when HWA infestations began, and by analyzing changes to canopy closure through available LiDAR data.

The evident decline in eastern hemlock populations in Southwestern Nova Scotia due to HWA infestations warrants targeted conservation efforts, not just through the treatment of infected trees, but also through the protection of eastern hemlock stands. Despite evidence showing that abundant species are typically excluded from conservation planning until threats to their populations emerge, a large portion of Nova Scotia's eastern hemlock are already being conserved through the Old-growth Forest Policy (Gerber 2016; Cornwall 2018, as cited in Degrassi *et al.*, 2019). The policy, however, only protects stands in which more than 20% of the basal area is comprised of trees greater than or equal to the reference age for the specific forest type (Nova Scotia, 2022). Young eastern hemlock stands and individual mature trees within secondary-growth forests are therefore not given the same protection, making them more vulnerable in the event of an HWA outbreak. The latter group, however, is protected in the sense that HWA does not spread as easily through mixed stands as it does through eastern hemlock dominated stands. Additionally, the policy only protects old-growth from logging activities, and does not necessarily protect trees against natural disturbances. Hence, it is crucial for the province to establish conservation strategies that will specifically target the protection of species affected by a known disturbance, which must be done immediately in order to control the spread of HWA and mitigate eastern hemlock mortality in Nova Scotia. Degrassi *et al.* (2019) developed a suggested framework for research, monitoring, management, and conservation of foundation species, which includes recommendations for long-term monitoring and conservation management. These strategies are largely centred around the early detection of threats, and restoring ecosystem interactions, functions, and services. Ultimately, conserving biodiversity among Nova Scotia's forests will help to limit the spread of HWA and slow the decline of eastern hemlock populations.

5.2. Future Uncertainty

Nova Scotia's eastern hemlock dominant forests are high in diversity, as shown by the results of this study. Due to certain limitations, the scope of this project, and in an attempt to avoid making assumptions, it is challenging to say with certainty what post-HWA successional pathways will look like in Nova Scotia. However, results show that regeneration opportunities will likely increase for intolerant hardwood species, suggesting that eastern hemlock, red maple, and white birch are likely to succeed in stands dominated by eastern hemlock. While some researchers have documented a decline in eastern hemlock regeneration post-HWA infestation, others have observed an overall increase in the frequency and cover of eastern hemlock seedlings (Orwig & Foster, 1998, Kizlinski *et al.*, 2002, Eschtruth *et al.*, 2006, as cited in Preisser *et al.*, 2011). Despite an observed increase in eastern hemlock seedlings in Southern plots, these seedlings will likely be even more vulnerable to HWA infestation, and may prolong an infestation or even cause a stand to be re-infested (Preisser *et al.*, 2011). In the event that eastern hemlock cannot successfully regenerate and canopy cover is significantly reduced, red maple will likely dominate as a shade intolerant species. However, if a significant number of overstory eastern hemlock trees survive HWA infestation, red spruce may thrive as a shade tolerant species.

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