Assessing the Impact of Insecticides on Hemlock Woolly Adelgids (*Adelges tsugae):* Implications for Eastern Hemlock (*Tsuga canadensis)* Conservation

By

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ABSTRACT

Eastern hemlock (*Tsuga canadensis*), a foundational species in North American forests, is under threat from the invasive hemlock woolly adelgid (HWA, *Adelges tsugae*). This study examines the impact of HWA infestation on eastern hemlock growth patterns in Kejimkujik National Park, Nova Scotia, through dendrochronological analysis. A total of 230 tree core samples were collected from treated and untreated stands to assess growth trends, tree health, and the effectiveness of systemic insecticide treatments. However, extreme rot and poor core integrity reduced the usable sample size to 15. Tree-ring analysis revealed fluctuating growth trends, with a period of increased growth in the mid-20th century followed by significant decline in recent decades, particularly after HWA detection in Nova Scotia in 2017.

Statistical comparisons between treated and untreated plots suggest that systemic insecticides may mitigate growth decline but do not significantly enhance tree diameter growth in the short term. Cross-dating with historical samples confirmed that growth suppression coincided with the arrival of HWA, emphasizing its impact on tree vitality.

These findings highlight the urgency of conservation efforts to protect eastern hemlocks from HWA-induced decline. While insecticides provide temporary relief, long-term solutions such as biological control and climate-adaptive forest management strategies must be prioritized. Future studies should continue monitoring tree-ring responses to treatment, assess climate-driven stressors, and evaluate the effectiveness of integrated pest management strategies. This research contributes to a growing body of literature on HWA management and forest resilience, informing conservation policies for eastern hemlock populations in Atlantic Canada.

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1.0 INTRODUCTION

1.1 Invasive Species

Invasive species have become one of the most severe ecological and socio-economic challenges worldwide, fundamentally altering ecosystems, reducing biodiversity, and imposing substantial economic costs on industries, including agriculture, forestry, and fisheries. The economic impacts are immense, with invasive species costing North American over $26 billion annually since 2010 (Diagne et al., 2021). As global trade and travel expand, so does the potential for non-native species to establish themselves in new environments, often with profound ecological consequences. The introduction of these species, whether accidental or intentional, can lead to rapid and uncontrollable population growth in areas where natural predators or environmental controls are lacking (Lodge et al., 2006). These invasive species can spread unchecked, outcompeting native species and destabilizing ecological relationships. The arrival of an invasive species can lead to trophic cascades, disrupting food webs and undermining the ecosystem services that humans rely on, such as water purification, carbon storage, and soil fertility (Vitousek et al., 1997). Addressing the impacts of invasive species is not only an ecological priority but also a critical societal concern, as these impacts ripple outward, affecting communities, economies, and human health (Lodge et al., 2006).

1.2 Hemlock Woolly Adelgids and Eastern Hemlocks

One invasive species with particularly far-reaching impacts in North America is the Hemlock Woolly Adelgid (*Adelges tsugae)*, commonly referred to as HWA, a tiny, sap-feeding insect native to East Asia that targets eastern hemlock (*Tsuga canadensis*) populations. Since its introduction to North America in the 1950s, HWA has become one of the most destructive forest pests, spreading rapidly through the eastern United States and parts of Canada and killing millions of hemlocks. Eastern hemlocks, often referred to as a foundational species, play a unique and irreplaceable role in forest ecosystems by shaping habitat conditions that support diverse species and by regulating water and nutrient cycles (Ellison et al., 2005). This shade-tolerant tree thrives in moist, cool environments and forms dense canopies that moderate understory conditions, creating stable microclimates that enable other shade-loving plants and moisture-dependent fauna to flourish (McMullin et al., 2008). The loss of eastern hemlocks due to HWA infestations is therefore likely to trigger a series of cascading effects within these ecosystems, impacting species composition, habitat availability, and broader forest dynamics (Orwig et al., 2002).

1.3 Ecological Consequences of HWA Infestation

The ecological impact of Hemlock Woolly Adelgid (HWA) extends far beyond the mortality of eastern hemlock trees. As HWA feeds on hemlock sap, it depletes the tree's resources, leading to needle loss, stunted growth, and ultimately death if infestations remain unmanaged (McClure, 1991). Unlike many other tree species, eastern hemlock lacks effective natural defenses against this pest, largely due to the absence of co-evolution with HWA, which is native to Asia (Havill & Montgomery, 2008).

HWA has a complex reproductive strategy that contributes to its rapid spread. It undergoes two generations of asexual reproduction (parthenogenesis) annually: the overwintering sistens generation and the spring progrediens generation. Eggs laid in early summer develop into sistens, which enter dormancy during hot weather and resume feeding in the fall. These mature and produce the progrediens generation in late winter, most of which continue the asexual cycle on hemlock hosts. This strategy, combined with passive dispersal by wind, birds, mammals, and human activity, has allowed HWA to spread aggressively across North American forests (Evans & Gregoire, 2007).

Eastern hemlock is considered a keystone species in many forest ecosystems due to its ability to regulate microclimates, soil composition, and stream flow. The death of hemlocks causes increased light penetration in forest understories, shifting competitive dynamics and favoring fast-growing, light-demanding deciduous trees (Orwig & Foster, 1998). These structural changes alter habitat conditions, reduce canopy density, and raise soil temperatures, which can significantly impact microbial communities and nutrient cycling processes (Ellison et al., 2005).

The ecological consequences cascade through multiple trophic levels. Forests impacted by HWA show reduced soil moisture and altered nutrient availability, often resulting in increased soil nitrogen levels (McClure, 1991). This favors nitrogen-loving plant species, potentially leading to long-term changes in forest succession and understory composition (reference needed). As a result, the decline of hemlock forests can facilitate secondary invasions by other non-native species, compounding ecological disruption and reducing overall biodiversity (Ellison et al., 2018).

The loss of eastern hemlock also extends to aquatic ecosystems. Hemlocks maintain cool, shaded conditions in riparian zones, which are critical for cold-water fish species such as brook trout (Salvelinus fontinalis). The removal of hemlock from these areas has been associated with increased stream temperatures, reduced oxygen levels, and shifts in macroinvertebrate communities (Tisler et al., 2009). These changes affect aquatic food webs and diminish the ecological integrity of freshwater habitats.

Overall, HWA-induced hemlock mortality has far-reaching ecological consequences. It alters forest structure, shifts competitive balances, disrupts hydrological and nutrient cycles, and impacts both terrestrial and aquatic biodiversity. These changes reduce ecosystem resilience and function, highlighting the importance of managing HWA to preserve the ecological roles that eastern hemlock forests provide (Kizlinski et al., 2002).1.4 Economic and Cultural Impacts of HWA

The implications of HWA infestations extend beyond ecological consequences to include economic and cultural losses. Hemlock forests are vital components of recreational landscapes, supporting outdoor activities such as hiking, camping, and fishing (Brantley et al., 2013). The aesthetic and cultural value of these forests, along with their economic contributions through ecotourism and timber resources, makes their rapid decline extremely concerning. Additionally, changes in forest composition can impact hydrology, increasing the frequency and severity of stream bank erosion and altering water temperatures, which can have negative consequences for aquatic ecosystems (Ross et al., 2003). These cascading effects highlight the urgency of understanding and mitigating the impacts of HWA to preserve the ecological integrity and functional benefits of hemlock forests (Orwig et al., 2012).

1.5 Biological Control

Research efforts have increasingly focused on biological control methods, particularly the introduction of predatory beetles that feed on HWA. The introduction of these beetles as a biological control strategy has shown promise in reducing HWA populations. In Nova Scotia, efforts have concentrated on the release of *Laricobius nigrinus*, a species of tooth-necked fungus beetle native to the Pacific Northwest, which preys exclusively on HWA (Nova Scotia Hemlock Conservation Initiative, 2023). In October 2023, researchers from Natural Resources Canada released these beetles in Shelburne, Queens, and Lunenburg Counties as part of a long-term strategy to mitigate infestations (Nova Scotia Hemlock Conservation Initiative, 2023). Studies in the northeastern United States suggest that *L. nigrinus* can establish stable populations and exert predation pressure on HWA, potentially reducing its impact on hemlocks over time (Havill et al., 2011).

However, the success of these biological control measures is reliant on several factors, including the beetles' adaptability to local climatic conditions and their successful integration into the existing ecosystem. Moreover, while *L. nigrinus* targets the winter stages of HWA, complementary predators like *Leucotaraxis* species— a specialist predator of HWA —which feed during the spring, may be necessary for a comprehensive control strategy (USDA Forest Service, 2024). Given the complexity of forest ecosystems and the variability of environmental conditions, ongoing research and long-term monitoring are essential to evaluate the efficacy and ecological impact of introducing *L. nigrinus* in Nova Scotia. Integrating biological control agents with other management strategies, such as chemical treatments and silvicultural practices, may offer a more robust approach to preserving eastern hemlock populations in the region.

1.6 Insecticide Applications

In response to the growing threat posed by Hemlock Woolly Adelgid (HWA), systemic insecticide treatments have become a key component in the management of eastern hemlock populations, particularly in high-value or conservation-priority areas of Nova Scotia. Two commonly used neonicotinoid insecticides are imidacloprid and dinotefuran, both of which have shown strong efficacy in reducing HWA populations by disrupting the insect's nervous system (Sheets, 2010). These chemicals are absorbed into the tree's vascular system—via soil drenching, trunk injection, or basal bark application—and are ingested by HWA as it feeds on sap, ultimately leading to death (McDonald et al., 2022; Benton et al., 2016).

Imidacloprid, the active ingredient in products such as Xytect 2F and IMA-Jet, binds to nicotinic acetylcholine receptors in the insect nervous system, causing paralysis and death. Soil drench applications of imidacloprid have demonstrated high efficacy and sustained protection, with detectable concentrations in foliage for up to seven years post-treatment (Cowles et al., 2006; Benton et al., 2016). Xytect 2F is typically applied via soil injection or basal trunk application and provides long-term protection, making it ideal for pre-emptive treatment in low- to moderate-infestation zones. In contrast, IMA-Jet is administered via trunk injection and is known for its faster uptake, delivering immediate but shorter-lived control, which is beneficial in areas with high HWA densities (Doccola et al., 2012; Steward & Horner, 2018).

Dinotefuran, another neonicotinoid, offers an alternative to imidacloprid, particularly in urgent treatment scenarios. Its higher water solubility allows for rapid absorption into the tree and quicker onset of HWA mortality, making it well-suited for situations where immediate pest suppression is necessary (Benton et al., 2016). However, dinotefuran degrades more quickly than imidacloprid, requiring more frequent applications to maintain effective protection (Joseph et al., 2011).

Despite their effectiveness, concerns persist regarding the environmental impacts of neonicotinoids. These include potential leaching into groundwater, negative effects on non-target organisms such as pollinators, and toxicity to aquatic invertebrates (Van Dyke et al., 2019). Consequently, insecticide use in Nova Scotia is strictly regulated and largely reserved for high-value conservation areas, including Kejimkujik National Park, where treatments are prioritized to preserve ecologically significant stands (Nova Scotia Department of Natural Resources, 2023). The selection of insecticide type and application method must therefore balance efficacy, environmental safety, and logistical feasibility within the broader framework of integrated pest management.

1.7 Dendrochronological Analysis in Assessing Invasive Species Impact

Dendrochronology, the scientific study of tree rings, serves as an ideal tool in ecological research, especially for understanding the impacts of HWA on hemlock ecosystems (Speer, 2010). By analyzing tree-ring patterns, researchers can reconstruct growth rates, assess long-term health of tree populations, and detect past disturbances (Cook & Kairiukstis, 1990). When looking at HWA infestations, dendrochronology allows for the precise dating of infestation events by identifying relevant changes in annual growth rings (Orwig & Foster, 1998). Such analyses have revealed that HWA significantly reduces radial growth in eastern hemlocks, with the severity correlating to the duration and intensity of infestation (Dukes et al., 2009). This method provides a physical structure to assess the progression of HWA infestation over time.

Moreover, dendrochronology facilitates the evaluation of forest stand dynamics by determining tree population age structures (Lorimer, 1985). This is crucial for understanding the alteration that invasive species cause to forest composition and succession patterns. For instance, by dating the formation of hemlock stands and identifying recruitment patterns, researchers can deduce how HWA-induced mortality influences the regeneration of native and non-native species within the ecosystem (Rentch et al., 2000).

Additionally, dendrochronological data can be integrated with climate records to sort the effects of invasive species from those of environmental factors on tree growth (Pederson et al., 2014). This approach allows for further understanding as to how HWA infestations interact with environmental stressors such as drought or temperature fluctuations, providing insights into the resilience and vulnerability of hemlock forests under changing climates (Ford & Vose, 2007).

1.8 Research Significance

The threat posed by HWA underscores the importance of understanding and mitigating the effects of invasive species in forested ecosystems. Research on HWA's impact on eastern hemlock is essential to guide conservation strategies and inform management practices aimed at preserving forest health and biodiversity. As eastern hemlock is foundational to the structure and function of many North American forests, its decline has implications not only for the species that rely directly on it but also for the broader environmental services these forests provide, from climate regulation to watershed stability (Foster, 2014).

Incorporating dendrochronological analysis into the study of HWA impacts develops our understanding of the temporal and spatial dynamics of infestations. It offers a retrospective lens to evaluate overall forest health, informs management strategies aimed to mitigate invasive species effects, and aids in predicting future forest responses to ongoing and concerning environmental changes (Ellison et al., 2018).

1.9 Objective

This research seeks to advance our understanding of the ecological consequences of HWA infestation by conducting a comparative study of eastern hemlocks in affected versus unaffected or managed areas within Kejimkujik National Park, with a particular interest in the growth patterns of hemlock plots that have been treated with insecticides versus those that have not. By analyzing variations in growth, reproduction, and ecosystem impact, this study aims to quantify the extent of HWA's influence on forest dynamics and to contribute data essential for developing effective conservation and restoration strategies. The findings of this study will not only enhance our understanding of HWA's ecological impact but also contribute to broader efforts in invasive species management and forest conservation, reinforcing the need for sustained monitoring and adaptive management approaches in the face of ongoing environmental threats.

2.0 STUDY REGION

2.1 Study Area

Kejimkujik National Park (44°26′ N, 65°12′ W) is located in southwestern Maitland Bridge, Nova Scotia, Canada, and encompasses approximately 404 km^2 of protected forest, wetlands, and waterways. The park is divided into two distinct regions: the inland portion, featuring the Acadian forest ecosystems, and the coastal region, which protects rare barrens and coastal habitats (Parks Canada, 2022). The inland section, where this study is conducted, is characterized by mixed-wood forests dominated by eastern hemlock (*Tsuga canadensis*), red maple (*Acer rubrum*), and eastern white pine (*Pinus strobus*), along with various rivers, lakes, and bogs supporting diverse biotas (Quinn & Hamilton, 2012).

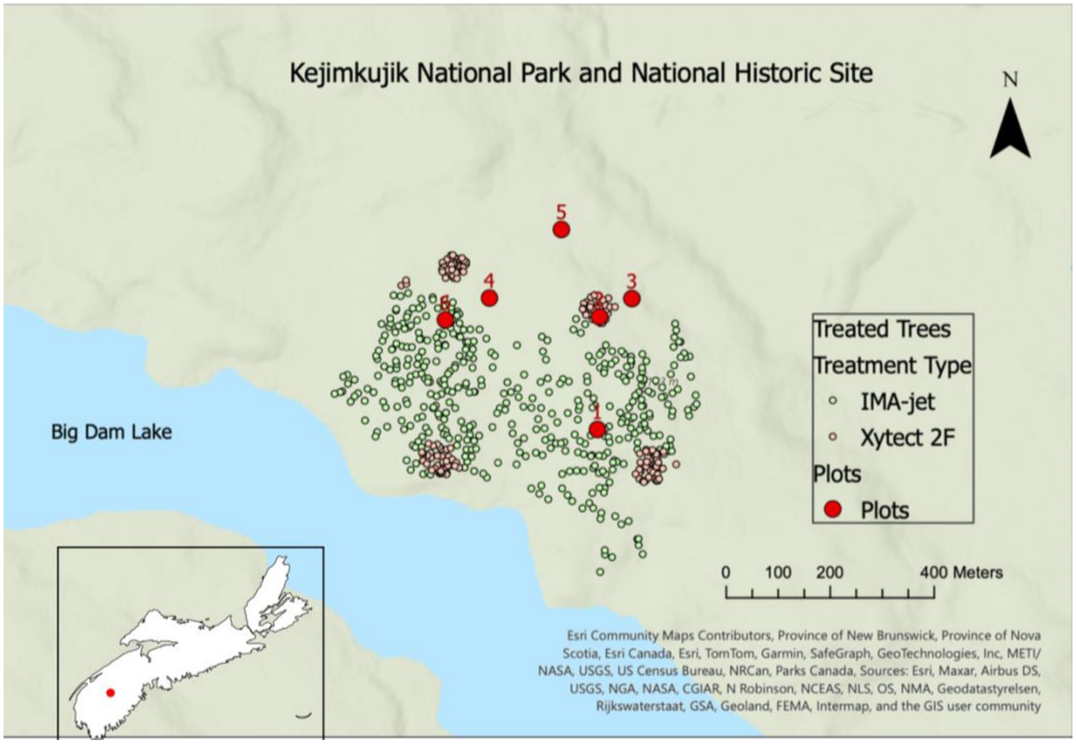

Figure 2.1 Map of the study area in Maitland Bridge, Nova Scotia, illustrating the distribution of study sites.

2.2 Sampling Site and Species

Within the Hemlocks and Hardwoods Trail, six sampling sites were chosen according to the following criteria (Figure 2.1). The site must: a) be a minimally managed forested area, b) contain a significant amount of the focal tree species as well as at least one red spruce, red maple, or white pine and c) be accessible for revisitation. Additionally, three of the six sites were selected based on having been treated with insecticides in recent years, while the remaining three sites had not received any insecticide treatments (Figure 2.1). Selection was conducted with the use of the 2022 Forest Ecosystem Classification (FEC) guidebook and a Geographic Information System (GIS).

The presence of a non-focal tree species was necessary to allow for a control species in each plot. The chemical composition and structural properties of control species such as red spruce, red maple, and white pine—including their sap composition and vascular systems—make them less conducive to HWA infestation, as the insect's feeding mechanisms are specifically adapted to the physiology of eastern hemlock (McClure, 1991; Havill & Montgomery, 2008; Havill et al., 2006). The presence of non-focal species also allowed for comparisons to be made between the impact of HWA on the growth of hemlocks versus unaffected tree species in the same ecosystems.

3.0 MATERIALS AND METHODS

3.1 Field Methods

At each plot, the geographic location was recorded and labeled using a unique Plot ID. Permanent plots were established for future tree core samples for further growth assessments.

Using a measuring tape, a circular canopy tree plot was made with a radius of 11.28 m^2 (0.04 ha). The measuring tape was placed on the wooden stake, where it started at magnetic North and was moved clockwise from the plot center. All trees with a diameter at breast height (DBH) $\geq$ 9.1 cm within this radius were tagged and numbered. In this study, breast height is defined as 1.3 meters (or 130 centimeters) above ground level, a standard measurement height used in forestry to account for variations in terrain and human height (Avery & Burkhart, 2002). The threshold was chosen to ensure consistency with commonly accepted forestry practices and to provide a standardized point of comparison for tree measurements. It allows for reproducibility and facilitates comparisons across studies and regions. Data recorded included:

- Tree number
- Species
- Status (alive or dead (snags))

- DBH
- Decay classification (only snags)

Two cores from each tree found in all six plots were taken using a 2-thread bit 5 mm diameter increment borer at breast height. Each core was glued to grooved, wooden mounting blocks, ensuring that the xylem was glued in a vertical orientation. Following mounting, each core was labeled and sanded using a hand sander with grit ranging from 150 to 400, selected based on the integrity of the tree core.

Figure 3.1 Glued and mounted core samples prior to sanding

Figure 3.2 WinDENDRO scan for tree ring analysis

3.2 Data Analysis

Data was taken to the Department of Natural Resources' Forestry Department in Truro, Nova Scotia for analysis. Each core was analyzed using WinDENDRO, an advanced image analysis system designed for precise tree ring measurement and evaluation. The cores were first scanned at high resolution, allowing for detailed visualization of tree ring structures. This high-resolution imaging enables the accurate measurement of tree ring widths down to 0.01 cm, ensuring precise annual growth analysis.

To maintain data accuracy, tree core samples that could not be reliably measured—such as those that were severely fragmented, missing significant portions, or structurally compromised—were removed from the dataset. This ensured that only well-preserved samples with clearly defined ring structures were used for analysis, minimizing errors and enhancing the reliability of the dendrochronological data.

Once the tree core data was processed using WinDENDRO, core samples were cross-dated against samples collected in Kejimkujik following Hurricane Dorian in 2019. This cross-dating analysis aimed to assess potential degradation in tree-ring structures and determine whether these changes were associated with Hemlock Woolly Adelgid (HWA) infestations or something else. Cross-dating involved aligning tree rings from different samples to a common timeline, allowing for the identification of shared growth patterns and enabling the detection of any disruptions in the tree-ring formation (Cook & Kairiukstis, 1990). This approach helped to establish a baseline of pre-infestation growth, enabling a more accurate interpretation of growth patterns and identifying any signs of HWA-induced stress, such as altered growth rates or ring anomalies.

The ring-width data was then processed in R using the dplR package to remove non-climatic growth trends, such as age-related growth patterns. A detrending process was applied using a spline function with the detrend() function in dplR. This method fits a growth trend to the raw ring width data, and residuals from this fit were used to compute the ring width index (RWI). The final RWI values were calculated by dividing each observed ring width by the fitted growth trend, standardizing the data with a mean of 1. To visualize the results, I used ggplot2 (Wickham, 2024) to generate plots of the raw ring width data and the detrended RWI. The raw measurements and the fitted growth trend were plotted using the plot function, while the standardized RWI values were displayed as a time series to examine long-term growth patterns. This standardization allows for direct comparison of growth trends across samples, enabling better interpretation of environmental and climatic influences on tree growth.

4.0 RESULTS

4.1 General Forest Structure

The mean live tree DBH varied among plots (Table 4.1), with treated plots showing a wider range of values (16.8 cm to 54.8 cm; Figure 4.1) compared to untreated plots (34.9 cm to 41.8 cm; Figure 4.1). Dead tree DBH was generally larger in untreated plots, with Plot 3 exhibiting the highest value at 76.8 cm. Dead tree DBH was generally larger in untreated plots, with Plot 3 exhibiting the highest value at 76.8 cm (Figure 4.1).

Table 4.1 Plot structural attribute values and species information

Plot #	**No. of eastern hemlocks**	**No. of red spruce**	**No. of white pine**	**No. of red maple**	**Mean DBH (cm)**	**Mean basal area (m2/ha)**
1	15	-	-	-	49.653	68.19
2	11	1	1	1	50.05	80.94
3	18	1	1	-	36.97	78.31
4	15	2	-	2	31.142	47.28
5	14	4	-	1	37.737	64.82
6	17	2	-	-	39.737	65.3
Avg.	15	2	1	1.333	40.882	67.473

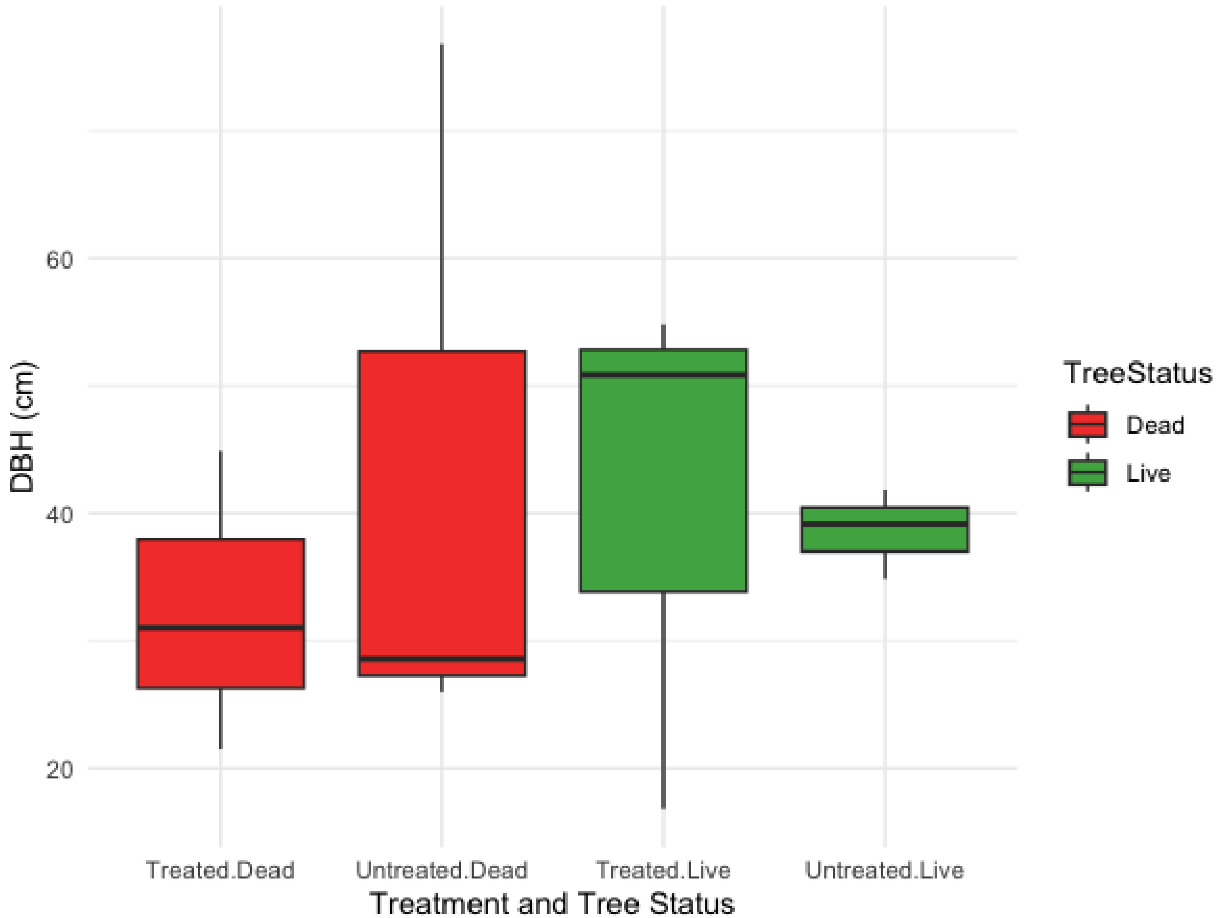

Fig. 4.1 Comparison of mean diameter at breast height (DBH) for live and dead trees across treated and untreated study plots. Boxplots illustrate differences in DBH between live and dead trees under each treatment condition, based on summary statistics from six plots. Treated plots generally show larger DBH in live trees compared to dead trees, while untreated plots exhibit more variability, particularly with larger DBH values in some dead trees.

4.2 Tree-Ring Growth Trends

A total of 230 tree cores were collected; however, only 15 were usable due to extreme rot or poor core extraction, which significantly limited the dataset for analysis. Within the usable cores, several distinct fluctuations in ring width were observed (Figure 4.2). For example, a period of increased growth was observed in the mid-20th century, followed by a decline in more recent decades.

Time-series analysis of older samples (Figure 4.3) highlights long-term growth variability, spanning from 1800 to the present. Growth rates exhibit both synchronous and asynchronous fluctuations among individual trees, suggesting potential environmental or site-specific influences. That variability appeared to increase in the latter half of the 20th century across multiple tree samples (Figure 4.4).

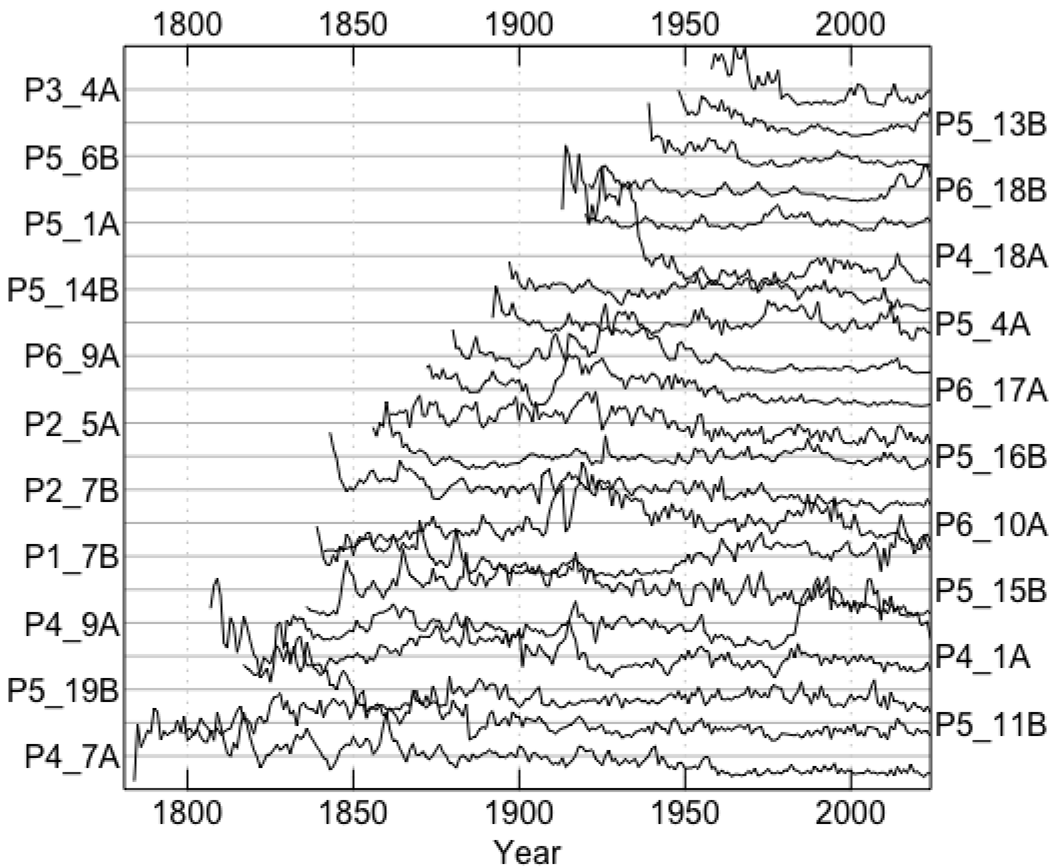

Fig. 4.2 A plot of tree-ring width measurements for the set of hemlock samples collected in 2024. Growth trends show variation among samples, with notable increases and decreases in growth rates around the mid-20th century.

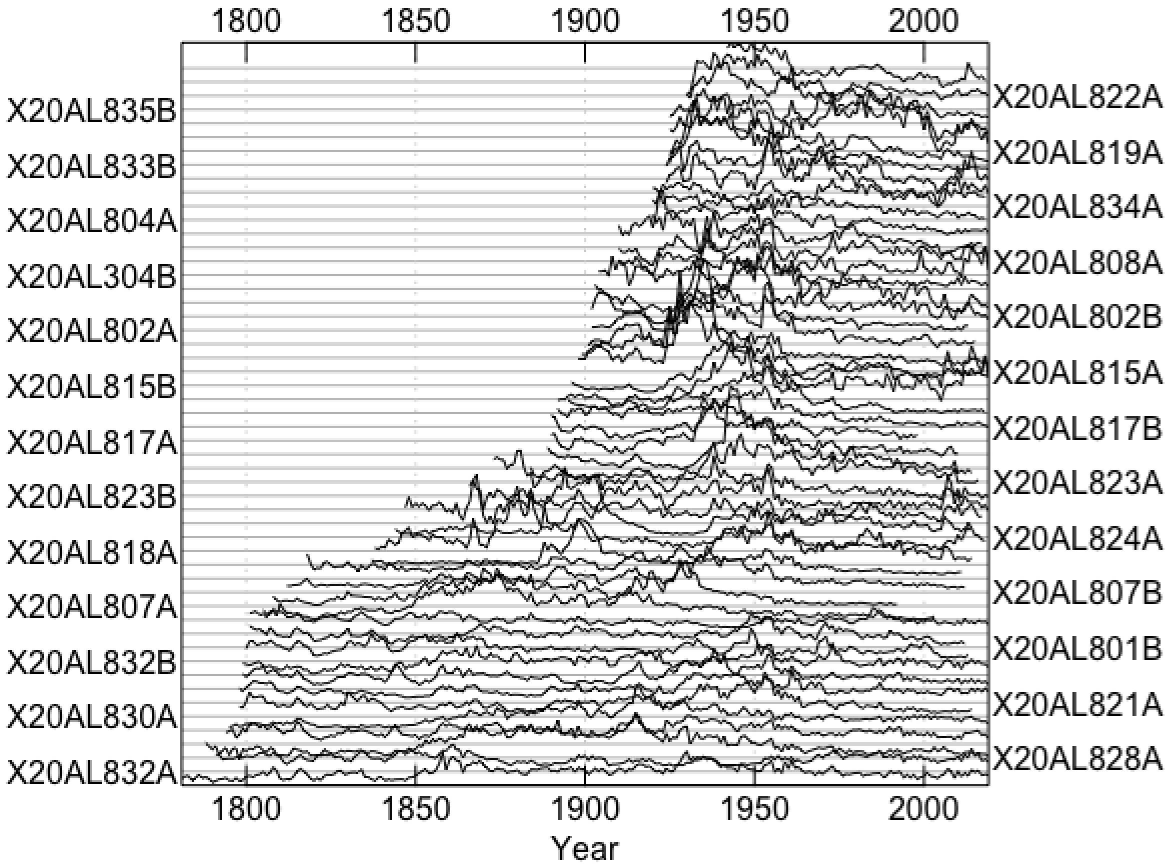

Fig. 4.3 Time series of tree-ring width measurements for multiple hemlock cross-dating samples from Mount Allison University. The plot spans from approximately 1800 to the present, showing growth trends and variability across different samples.

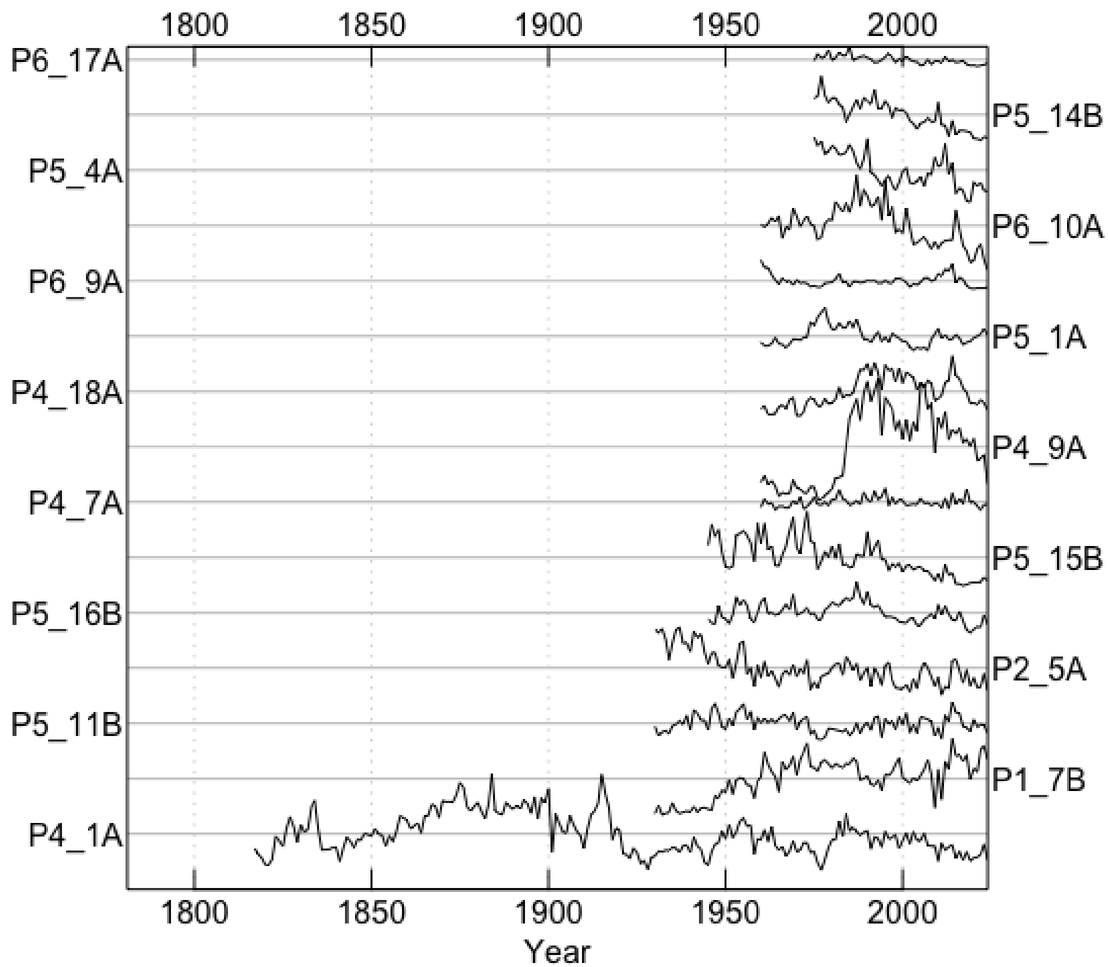

Fig. 4.4 A time-series plot displaying multiple labeled data series across the years from 1800 to 2000. Each line represents a different dataset (e.g., P6_17A, P5_4A, etc.), showing trends over time. The y-axis labels correspond to different data series, while the x-axis represents the year. The plot suggests an increase in variability and values in the latter half of the 20th century.

4.3 Cross-dating and Chronology Validation

To assess the accuracy of tree-ring dating, skeleton plots were constructed (Figure A.3). Cross-dating revealed strong agreement among samples, with marker years aligning across multiple trees. Interseries correlation analysis (Figure 4.6) showed temporal fluctuations in growth synchrony, with stronger correlations during specific periods. This indicates phases of shared environmental stress or recovery, potentially linked to regional climate conditions or, more recently, HWA infestations.

4.4 Relationship Between Growth, Climate, and HWA Infestation

Differences in individual tree chronologies suggest that while insecticide-treated trees (e.g., P49A) exhibited more stable or even increased growth patterns in recent decades, untreated trees (e.g., P514B) showed a marked decline, potentially due to prolonged hemlock woolly adelgid (HWA) stress.

Ring width measurements (Figure 4.5) highlight these trends, with treated trees maintaining or improving ring width, while untreated trees declined significantly. These patterns are not unique to P49A and P514B, but are representative of most core samples analyzed. This suggests that insecticide treatments may help mitigate the decline associated with HWA infestation, maintaining typical growth levels even if they do not enhance growth beyond baseline expectations.

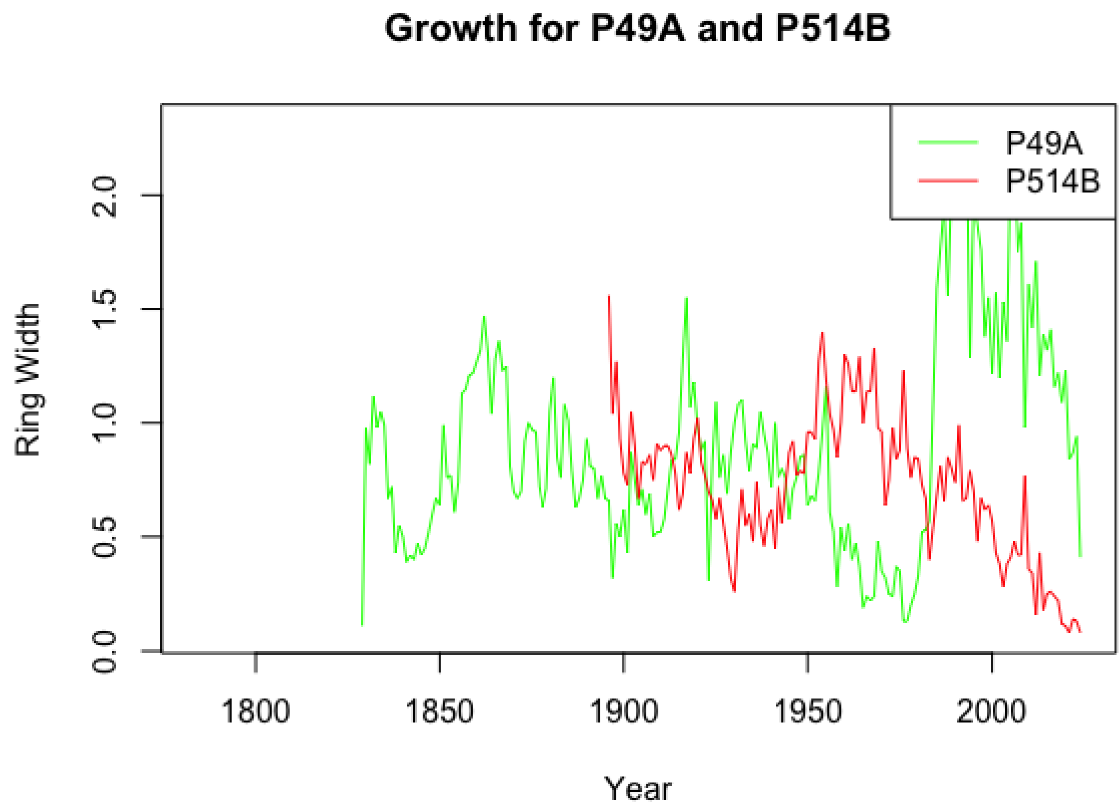

Fig. 4.5 Ring width growth over time for trees P49A and P514B. The green line represents P49A, while the red line represents P514B. Growth is measured as ring width (mm) from the early 1800s to the 2000s. Both trees show periods of fluctuating growth, with a marked decline in P514B relative to P49A in recent decades. These patterns are consistent with trends observed in most other core samples from the same site.

5.0 DISCUSSION

5.1 Impact of Insecticide Treatments on Eastern Hemlock Growth

The similarity in forest structure between treated and control plots suggests that plot areas may have originated from a comparable disturbance and experienced similar forest succession. The control plots contain a proportionate number and size distribution of live trees, indicating that HWA infestations have not yet caused substantial mortality in untreated areas. This observation contrasts with studies in areas with longer infestation histories, where HWA-induced mortality has significantly altered stand composition (Orwig & Foster, 1998; Orwig et al., 2002). If significant tree loss had occurred in the control plots, this would likely be reflected in a higher number of snags compared to the treated plots, which is documented in heavily infested sites (Krapfl et al., 2011).

While insecticide treatments did not lead to increased DBH in this study, it is possible that treatments contribute to long-term preservation by mitigating the decline associated with HWA infestations. Since HWA causes progressive deterioration in eastern hemlocks, the primary goal of insecticide treatments is to halt or slow this decline rather than stimulate excessive growth (McClure, 1991; Cowles et al., 2006). Due to this, long-term monitoring will be necessary to determine whether treated trees exhibit improved health and growth over time. Future research should include detailed site assessments to evaluate how these factors interact with treatment effectiveness and hemlock recovery. Studies have also shown that insecticide treatments can influence nutrient cycling and ecosystem processes in forests, potentially altering competitive interactions among tree species (Brantley et al., 2013). Investigating these broader ecosystem effects will be crucial in understanding the long-term viability in chemical control strategies.

5.2 Tree-Ring Growth Patterns and Environmental Influences

Tree-ring width analysis revealed fluctuating growth trends among hemlock samples, with a notable increase in the mid-20th century followed by a decline in more recent decades (Figure 4.2). The consistency of peaks and valleys in growth patterns across trees of varying ages and locations suggests that external environmental factors likely influenced hemlock growth, as such synchronized changes are unlikely to occur in the absence of a uniform external influence. Increased variability observed in tree growth from 1950 onward (Figure 4.4) may correspond to broader climatic changes, including rising temperatures and shifts in increased frequency of drought and altered seasonal rainfall patterns, both of which have been documented in other dendrochronological studies (Pederson et al., 2014; Orwig & Foster, 1998). Eastern hemlocks are particularly vulnerable to increasing climate variability because their shallow root systems and shade tolerance make them sensitive to drought stress and temperature extremes, potentially contributing to the observed declines in growth (Brookes et al., 2017)

Given that eastern hemlocks are sensitive to changes in temperature and moisture availability, continued warming trends could exacerbate stress on these trees, making them more vulnerable to HWA infestation. Similar studies in the Appalachian region have demonstrated a correlation between increased summer temperatures and reduced hemlock growth rates, particularly in already infested stands (Brantley et al., 2013). Further research incorporating climate models and tree-ring analysis could help clarify the extent to which environmental change influences hemlock health and resilience. Additionally, studies suggest that the physiological effects of HWA infestation, such as reduced photosynthetic capacity and altered carbon allocation, may compound climate-related stressors (Miniat et al., 2020). By integrating physiological and ecological research, a more comprehensive understanding of hemlock decline may be developed.

5.3 Cross-Dating and Chronology Reliability

The cross-dating analysis (Figure 4.5) confirmed high levels of agreement among tree-ring samples, validating the accuracy of growth trend assessments. Periods of reduced correlation may indicate localized disturbances or variation in individual tree responses to specific stressors, such as HWA infestation. These fluctuations suggest that hemlocks, like other species, may exhibit varying levels of susceptibility to biotic and abiotic pressures, but that environmental stressors are likely the primary drivers of synchronous growth changes across trees. (Miniat et al., 2020). These variations reinforce the importance of site-specific analyses when assessing the impact of HWA and other environmental stressors.

The presence of marker years —years in which abrupt growth reductions were observed across multiple samples — suggests separate or unrelated events that may have individually influenced hemlock growth, rather than a continuous or connected series of factors. These could include severe droughts, pest outbreaks, or human-induced disturbances. A more in-depth exploration of these events using historical climate data and ecological records could provide further insights into factors influencing hemlock growth trajectories. Studies have also shown that cross-dating can help detect subtle growth anomalies linked to insect defoliation, making it a valuable tool in long-term forest health monitoring (Vieira et al., 2013).

5.4 Management Strategies

The introduction of predatory beetles, such as *Laricobius nigrinus*, has emerged as a potential biological control strategy for mitigating HWA invasions. Previous studies have demonstrated that *L. nigrinus* can effectively reduce HWA densities in some regions (Havill et al., 2011; Vieira et al., 2013). However, the efficacy of these beetles in Nova Scotian forests remains uncertain due to climatic differences and prey availability.

Studies have shown that *L. nigrinus* populations can establish and persist in areas with moderate winter temperatures, but their impact on HWA suppression varies depending on environmental conditions (Mausel et al., 2010). The colder winter temperatures in Nova Scotia may limit beetle survival and reproduction, reducing their effectiveness as a biological control agent. Furthermore, the slow reproductive rates of these beetles may delay population establishment, resulting in the need for repeated introductions and monitoring (Havill et al., 2011).

Despite these challenges, the use of biological control remains a promising component of an integrated pest management strategy. A combination of insecticide treatments and biological control efforts may provide a more sustainable approach to managing HWA infestations. Future research should expand upon evaluating the survival, dispersal, and predation rates of introduced beetle species in Nova Scotia to determine their long-term viability.

While treated trees exhibited relatively stable growth patterns, untreated trees displayed a greater degree of decline, particularly in recent years. This suggests that systemic insecticide treatments may help mitigate the negative effects of HWA infestations, but do not necessarily promote increased growth beyond expectations. The ring width growth (Figure 4.5) further supports this conclusion, as treated trees maintained stable growth trends, whereas untreated trees experienced a noticeable decline. These findings align with previous research indicating that insecticide treatments primarily serve to preserve existing tree health in the short term, rather than stimulate accelerated growth. Given that it can take several years for coniferous trees to regrow defoliated crowns and replenish depleted reserves, any benefit from treatment may be temporary, particularly after prolonged infestations (McClure, 1991; Cowles et al., 2006).

One consideration for future studies is the potential for variation in treatment efficacy across different environmental conditions. Factors such as soil moisture, insecticide uptake rates, and the frequency of reapplication could all influence outcomes (Eschtruth et al., 2013). Furthermore, the potential for insecticide resistance in HWA populations should be monitored over time, as repeated exposure to chemical treatments may lead to adaptive changes within the pest population (Havill et al., 2011). Long-term studies are necessary to evaluate the sustainability of insecticide use in hemlock conservation strategies.

5.6 Conservation Implications and Future Research

The implications of these findings for eastern hemlock conservation are significant. Tree ring analysis reveals a decline in hemlock health beginning around 2017 and 2018, coinciding with the first detection of HWA in Nova Scotia and in Kejimkujik National Park, respectively (Nova Scotia Department of Natural Resources and Renewables [NSDNRR], n.d.; Parks Canada, n.d.). This suggests that HWA infestation has already had a measurable impact and underscores the urgency of proactive, resistance-based conservation strategies to mitigate further losses.

While systemic insecticides offer a means of slowing HWA-induced decline—as demonstrated by the more stable growth patterns in treated trees such as P49A—these treatments require consistent application and monitoring. Insecticides alone may not constitute a viable long-term solution, particularly in unmanaged forest stands where logistical constraints limit feasibility. Moreover, the repeated use of systemic insecticides raises valid concerns about unintended environmental consequences. Although these compounds are designed to target HWA specifically, they may affect non-target organisms, including beneficial insects, pollinators, soil microbiota, and aquatic life in the event of runoff (Tišler et al., 2009; Bentz et al., 2002). Future research should continue to evaluate these ecological risks to ensure that insecticide use does not compromise broader forest ecosystem health.

In addition to chemical control, integrating biological agents is vital for large-scale and sustainable management. However, the long-term success of biological control has been mixed. The establishment of predator populations, such as Laricobius spp., has proven inconsistent, limiting their widespread efficacy (Havill et al., 2014). Continued research is needed to improve predator release strategies and to develop integrated pest management approaches that combine chemical and biological control more effectively.

Genetic resistance represents another critical avenue for conservation. Some eastern hemlock populations have shown natural resistance to HWA, and screening these trees for selective breeding could offer a more durable solution. Scaling up resistance breeding and integrating it with reforestation and silvicultural practices could help maintain healthy hemlock populations over the long term (Lodge et al., 2006).

Climate change adds further complexity to eastern hemlock conservation. Rising temperatures and shifting precipitation regimes may exacerbate tree stress and alter HWA population dynamics, potentially undermining existing control strategies. Research into climate-resilient conservation approaches—such as assisted migration, genetic diversification, and habitat restoration—will be essential to enhance the adaptive capacity of hemlock forests. A follow-up study of these research plots in three to five years is recommended to assess changes in forest structure and tree ring growth, which would offer deeper insight into the long-term effects of various management strategies.

5.7 Conclusion

This study contributes to the growing body of research on eastern hemlock conservation by demonstrating the potential benefits and limitations of insecticide treatments in mitigating the impact of HWA infestations. While insecticides provide a means of stabilizing tree health in the short term, their long-term efficacy and sustainability require further investigation. A multifaceted conservation approach that integrates chemical, biological, and genetic strategies will be essential for ensuring the persistence of eastern hemlock populations. Continued monitoring and adaptive management strategies will be crucial in safeguarding this foundational species against the ongoing threat of HWA and broader environmental stressors.

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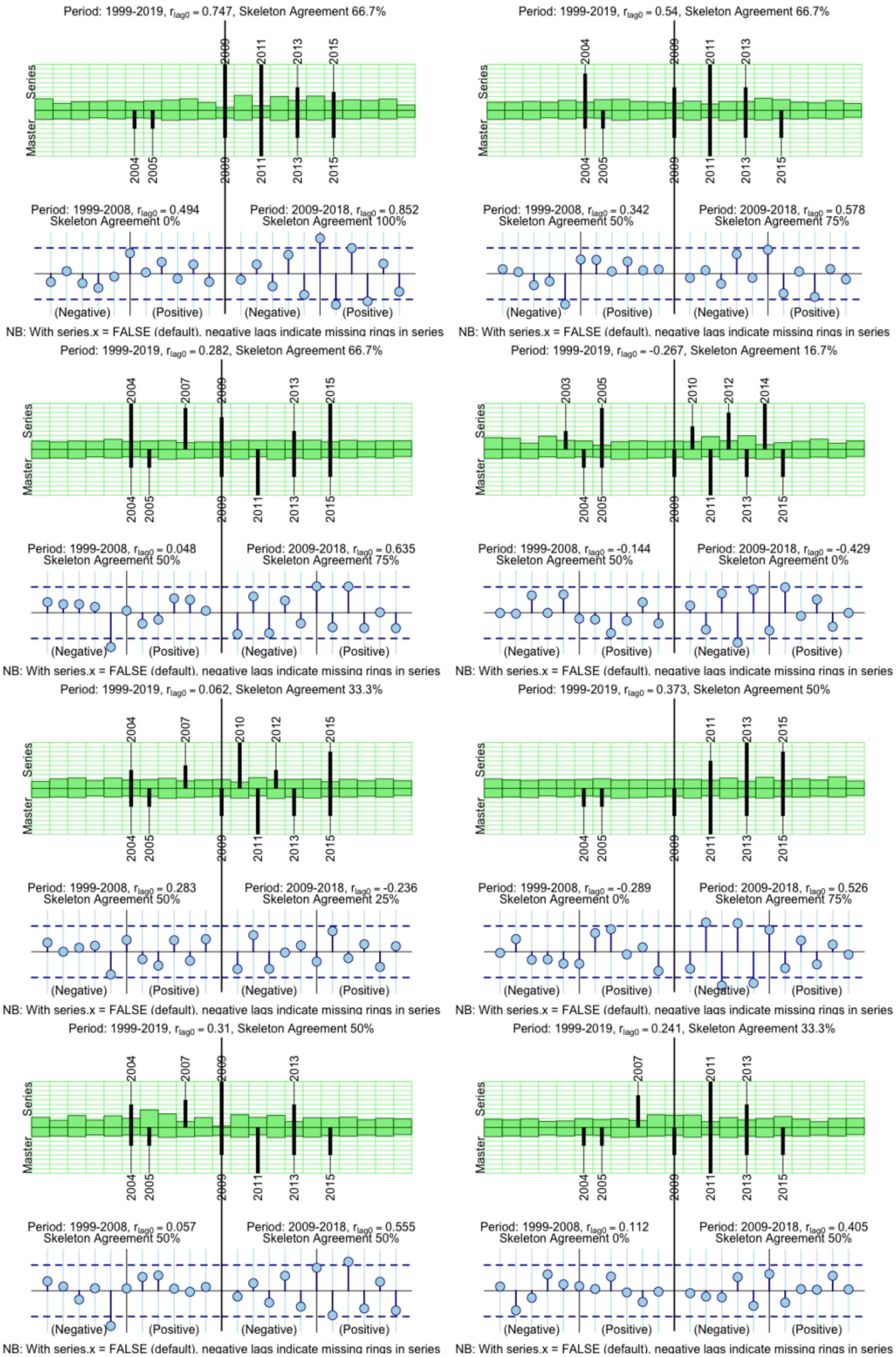
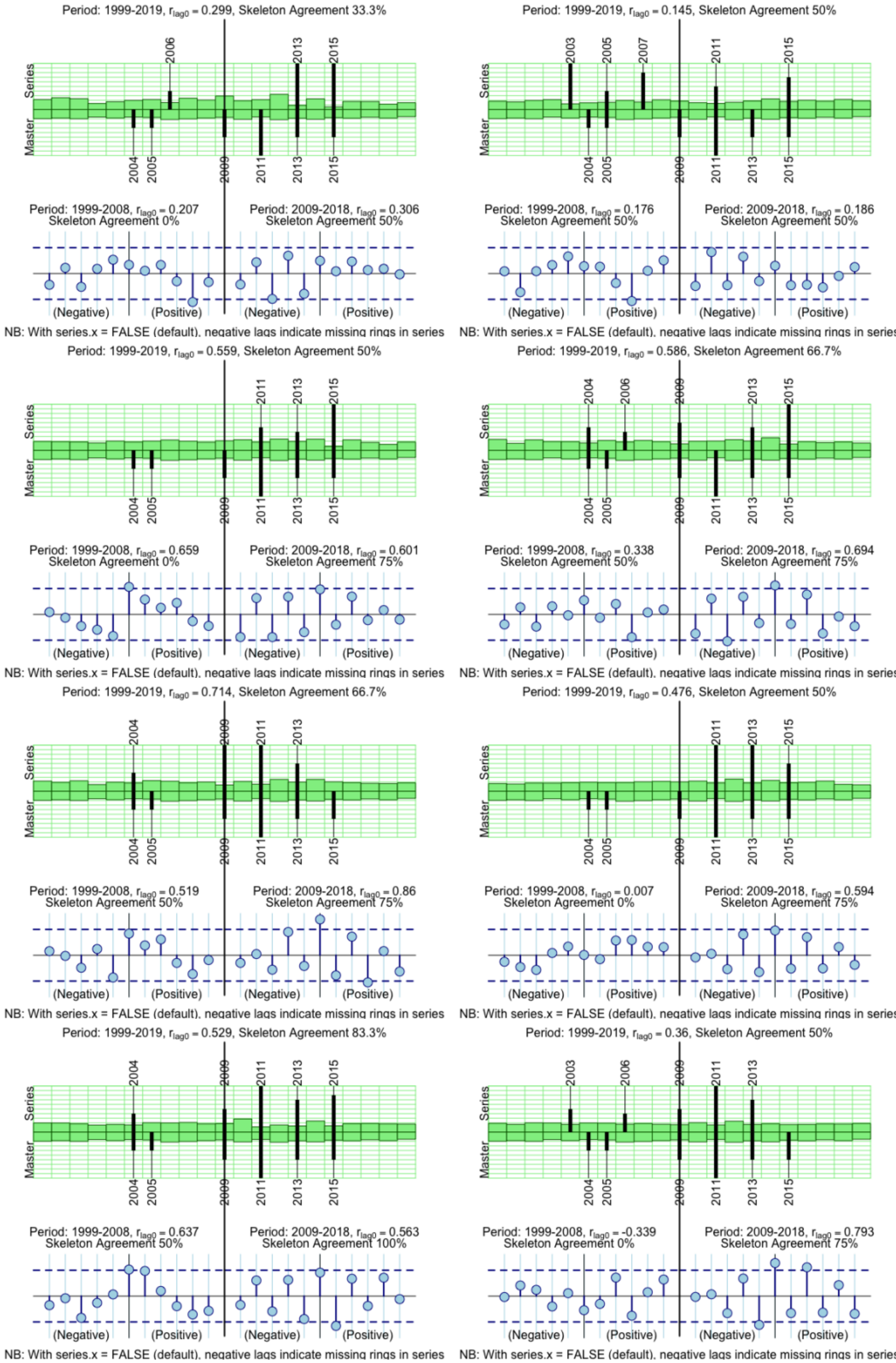
7.0 APPENDIX

Figure A.1 Sampling with a 5.1mm increment borer

Figure A.2 Tree core example



Period: 1999-2019, r_{lag0} = 0.747, Skeleton Agreement 66.7%
Period: 1999-2008, r_{lag0} = 0.494
Skeleton Agreement 0%
Period: 2009-2018, r_{lag0} = 0.852
Skeleton Agreement 100%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.54, Skeleton Agreement 66.7%
Period: 1999-2008, r_{lag0} = 0.342
Skeleton Agreement 50%
Period: 2009-2018, r_{lag0} = 0.578
Skeleton Agreement 75%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.282, Skeleton Agreement 66.7%
Period: 1999-2008, r_{lag0} = 0.048
Skeleton Agreement 50%
Period: 2009-2018, r_{lag0} = 0.635
Skeleton Agreement 75%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = -0.267, Skeleton Agreement 16.7%
Period: 1999-2008, r_{lag0} = -0.144
Skeleton Agreement 50%
Period: 2009-2018, r_{lag0} = -0.429
Skeleton Agreement 0%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.062, Skeleton Agreement 33.3%
Period: 1999-2008, r_{lag0} = 0.283
Skeleton Agreement 50%
Period: 2009-2018, r_{lag0} = -0.236
Skeleton Agreement 25%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.373, Skeleton Agreement 50%
Period: 1999-2008, r_{lag0} = -0.289
Skeleton Agreement 0%
Period: 2009-2018, r_{lag0} = 0.526
Skeleton Agreement 75%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.31, Skeleton Agreement 50%
Period: 1999-2008, r_{lag0} = 0.057
Skeleton Agreement 50%
Period: 2009-2018, r_{lag0} = 0.555
Skeleton Agreement 50%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.241, Skeleton Agreement 33.3%
Period: 1999-2008, r_{lag0} = 0.112
Skeleton Agreement 0%
Period: 2009-2018, r_{lag0} = 0.405
Skeleton Agreement 50%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series


Period: 1999-2019, r_{lag0} = 0.299, Skeleton Agreement 33.3%
Period: 1999-2008, r_{lag0} = 0.207
Skeleton Agreement 0%
Period: 2009-2018, r_{lag0} = 0.306
Skeleton Agreement 50%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.145, Skeleton Agreement 50%
Period: 1999-2008, r_{lag0} = 0.176
Skeleton Agreement 50%
Period: 2009-2018, r_{lag0} = 0.186
Skeleton Agreement 50%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.559, Skeleton Agreement 50%
Period: 1999-2008, r_{lag0} = 0.659
Skeleton Agreement 0%
Period: 2009-2018, r_{lag0} = 0.601
Skeleton Agreement 75%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.586, Skeleton Agreement 66.7%
Period: 1999-2008, r_{lag0} = 0.338
Skeleton Agreement 50%
Period: 2009-2018, r_{lag0} = 0.694
Skeleton Agreement 75%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.714, Skeleton Agreement 66.7%
Period: 1999-2008, r_{lag0} = 0.519
Skeleton Agreement 50%
Period: 2009-2018, r_{lag0} = 0.86
Skeleton Agreement 75%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.476, Skeleton Agreement 50%
Period: 1999-2008, r_{lag0} = 0.007
Skeleton Agreement 0%
Period: 2009-2018, r_{lag0} = 0.594
Skeleton Agreement 75%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.529, Skeleton Agreement 83.3%
Period: 1999-2008, r_{lag0} = 0.637
Skeleton Agreement 50%
Period: 2009-2018, r_{lag0} = 0.563
Skeleton Agreement 100%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Period: 1999-2019, r_{lag0} = 0.36, Skeleton Agreement 50%
Period: 1999-2008, r_{lag0} = -0.339
Skeleton Agreement 0%
Period: 2009-2018, r_{lag0} = 0.793
Skeleton Agreement 75%
NB: With series.x = FALSE (default), negative lags indicate missing rings in series
Series
Master
(Negative)
(Positive)

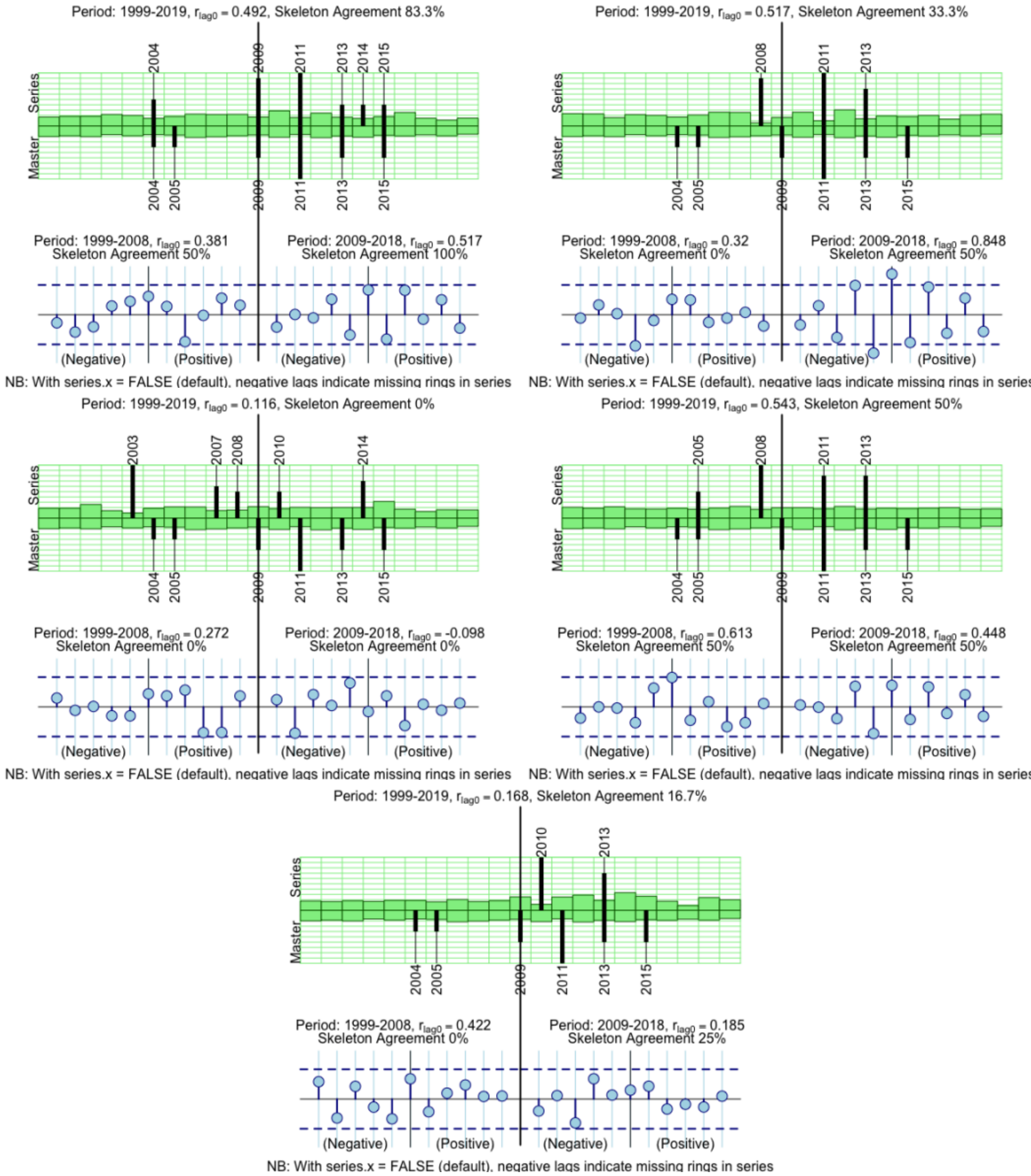


Figure A.3 Skeleton plots for tree-ring cross-dating of samples. Top half shows master chronology (green) with black bars indicating significant marker years. Lower half presents the cross-dating diagnostics, including correlation values (*r_{lag0}*) and skeleton agreement percentages for different periods.