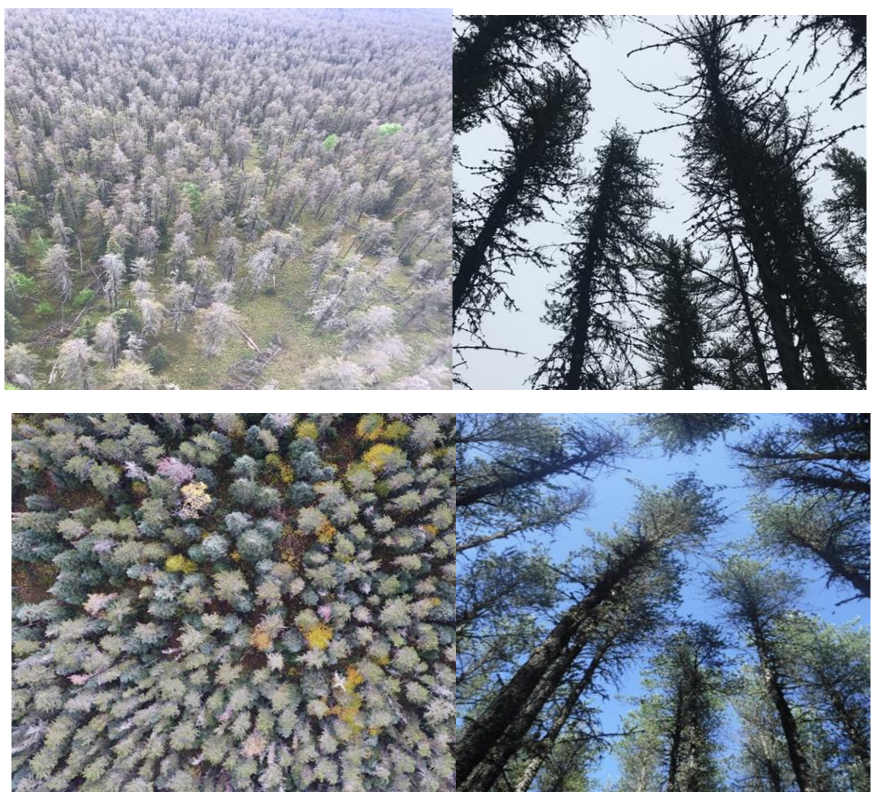
Tracking stand-level responses (mortality and recovery) in jack pine (*Pinus banksiana Lamb.)*-dominated stands following the recent jack pine budworm (*Choristoneura pinus pinus F.)* infestation across northwestern Ontario

FACULTY OF NATURAL RESOURCES MANAGEMENT
LAKEHEAD UNIVERSITY
THUNDER BAY, ONTARIO

BY

Stephanie Lacey



April 18, 2023

Tracking stand-level responses (mortality and recovery) in jack pine (*Pinus banksiana L.)*-dominated stands following the recent jack pine budworm (*Choristoneura pinus pinus F.)* infestation across northwestern Ontario

By

Stephanie Lacey

An Undergraduate Thesis Submitted in
Partial Fulfillment of the Requirements for the
Degree of Honours Bachelor of Science in Forestry
(or Degree of Honours Bachelor of Environmental Management)

FACULTY OF NATURAL RESOURCES MANAGEMENT
LAKEHEAD UNIVERSITY
THUNDER BAY, ONTARIO

April 18, 2023

Dave Morris
Major Advisor

Matthew Corbett
Second Reader

LIBRARY RIGHTS STATEMENT

Signature: ________________________________

Date: ____________________________________

A CAUTION TO THE READER

This HBScF thesis has been through a semi-formal process of review and comment by at least two faculty members. It is made available for loan by the Faculty of Natural Resources Management for the purpose of advancing the practice of professional and scientific forestry. The reader should be aware that opinions and conclusions expressed in this document are those of the student and do not necessarily reflect the opinions of the thesis supervisor, the faculty, or Lakehead University.

MAJOR ADVISOR COMMENTS

ABSTRACT

This study investigates the stand-level responses (mortality and recovery) in jack pine-dominated forests following a recent infestation of the jack pine budworm across northwestern Ontario. The aim is to understand the extent and severity of the infestation's impact on these forests and to identify potential factors influencing the response of the stands. The research utilizes field data collected from 2019 to 2022, including tree mortality surveys and forest inventory assessments. The results show that the budworm infestation has caused changes in natural mortality in the stands. The results have shown a significant difference in crown density, whereas live tree density shows insignificant differences from 2020 to 2022. The overall diameter distribution between the JPBW stands and control stands showed that the control site had a higher diameter and volume over all and continued to grow over time whereas the JPBW stands maintained a similar distribution over time. Factors such as stand density, site quality, and diameter distributions are found to influence the stands' response to the infestation. The findings and literature indicate that a commercial thin of the affected stands could prove to be beneficial in preserving stands as a whole and creating short term profit.

Table of Contents

LIST OF FIGURES

ACKNOWLEDGMENT

I would like to express my sincere gratitude and appreciation to everyone who supported me during my research work and helped me to successfully complete this thesis.

First and foremost, I would like to thank my thesis advisor, Dave Morris, for their invaluable guidance, support, and encouragement throughout this journey. Their expertise, knowledge, and insight were instrumental in shaping my research direction, methodology, and analysis. I would like to extend my gratitude to Matthew Corbett who was my second reader.

I would also like to thank my colleagues and friends who provided me with valuable feedback, ideas, and support during my research work. Their constructive criticism and encouragement were invaluable in shaping my research ideas and keeping me motivated during challenging times.

I am grateful to the Lakehead University for providing me with the necessary resources, facilities, and opportunities to carry out this research work.

Finally, I would like to express my heartfelt gratitude to my family for their, support, and encouragement throughout my academic journey. Their constant encouragement and support helped me to overcome various obstacles and reach this milestone.

Thank you all for your contributions and support, without which this thesis would not have been possible.

ABSTRACT

This study investigates the stand-level responses (mortality and recovery) in jack pine-dominated forests following a recent infestation of the jack pine budworm across northwestern Ontario. The aim is to understand the extent and severity of the infestation's impact on these forests and to identify potential factors influencing the response of the stands. The research utilizes field data collected from 2019 to 2022, including tree mortality surveys and forest inventory assessments. The results show that the budworm infestation has caused changes in natural mortality in the stands. Factors such as stand density, site quality, and diameter distributions are found to influence the stands' response to the infestation. The findings provide valuable insights into the long-term effects of budworm infestations on jack pine-dominated forests and can inform future management strategies to mitigate the impacts of these disturbances. With proper understanding the goal is to determine best management practice in the future to minimize the impacts of JPBW outbreaks.

INTRODUCTION

For the boreal forest fire is the primary disturbance mechanism with approximately 1% of boreal forest burned annually although predicted to increase due to climate change these shifts in disturbance regimes in size severity frequency (Gill, 2014). Under accelerating rates of climate change may lead to unprecedented consequences for ecosystem recovery and resilience and have the potential to trigger abrupt ecosystem transitions. Annually wildland fires near northern communities can create unfavourable living conditions destroy or endanger assets an infrastructure because of catastrophic fires Wildland fire behavior is influenced by weather fuel loadings geography an access. Beyond wildfire there are other natural disturbance agents in the boreal forest that include cyclical out breaks of the jack pine budworm (JPBW) previous outbreaks have resulted in frequent and large wildfires increasing regional concerns of the cumulative effects associated with the current JPBW outbreak across northwestern Ontario. For example, there have been 67 forest fire ignitions that have occurred in jack pine budworm affected regions during the 2018 and 2019 fire seasons with an additional 10 fires extending across impacted stands that total approximately 57,000 hectares (Gill, 2014).

There are remains considerable uncertainty as to how much Jack pine budworm influences wildfire danger and risks in landscapes dominated by Jack pine forest stands (McCullough, 2000). Jack pine budworm defoliation has been shown to cause accelerate in stand mortality 2 to four years after recurring defoliation. The accumulation of fine and forest floor fuels provides optimal service surface fire conditions through the enhancement of forest fuel loadings in these JPBW affected stands. In this damage stand the shattering of dead tops and windthrow introduces ladder fuels into the crown of remaining live trees thereby increasing surface fire intensity and crown fire potential. It is anticipated that these JPBW affected stands will have larger increased surface fuel loads higher rates of tree mortality and a higher proportion of top killed trees. With the opening of the forest canopy there is potential for fine fuels and the forest floor to dry out quicker and two a greater extent following rainfall events in these JPBW affected stands compared to unaffected closed canopy stands thereby altering wildfire behavior that in turn may alter fire suppression efforts (McCullough, 2000).

OBJECTIVE

Study objective: To examine stand structural characteristics (e.g., tree mortality/recovery, crown vigour, release) out to post three years following jack pine defoliation as compared to unaffected jack pine stands. Here our hypothesis is that JPBW-affected will have higher forest fuel loadings, higher rates of tree mortality (i.e., more standing dead trees), and more top-killed trees, and the fine fuels and the forest floor (duff) will dry out quicker in the budworm-affected jack pine stands than in unaffected, closed-canopy stands.

LITERATURE REVIEW

Jack pine life cycle

Jack pine commonly regenerates after wildfires with its life strategy of generating to serotinous cones that open under extreme heat (i.e., opening resin-boned cones to release protected seeds. The Jack Pine Budworm is a well-adapted parasite that is a regular component of the Pine natural disturbance cycle (Desponts & Payette, 1991) (Farrar, 2017). The jack pine budworm is a well-adapted parasite that is a cyclical component of jack pine's natural disturbance cycle stand-replacing fire is more likely, and the fuel load is increased when jack pine is killed by budworms, which also causes jack pine to regenerate more vigorously. When conditions are appropriate for seed germination and seedling establishment, successful regeneration occurs (Desponts and Payette, 1991, Farrar, 2017). The distribution of forest stands is influenced by other biological factors in more southern regions, where the direct impact of temperature is less apparent competition, soil conditions, and fire regime are few examples of whether they are well suited for it. The mechanisms of communities in boreal coniferous forests are largely regulated by recurring fires jack pine (*Pinus banksiana Lamb.*) appears to be an example of this. jack pine's geographic range matches that of the Canadian boreal forest. The other hand, jack pine has a limited lifespan and is shade-intolerant (Desponts and Payette, 1991, Farrar, 2017).

Jack pine budworm life cycle

Jack pine bud worm (JPBW) has been documented through regional forest health survey program in North America since the 1950's. JPBW (*Choristoneura pinus pinus Free.)* is native to North America and is the main defoliator of jack pine (Pinus banksiana. Lamb). In terms of its life cycle, budworm the jack pine budworm lifecycle Larvae of the second instar emerge from beneath the bark scales in late May or early June. After emerging from the male pollen flowers, the larvae begin feeding on the developing needles of new shoots. Late June and early July are the main feeding times. Mature jack pine budworm is approximately the 21mm long, with reddish-brown bodies with yellowish sides and reddish-brown heads and of the mature larvae have two rows of white dots on their backs. Pupation takes place on the stalk or during the needles from July to early August. In the mid to late July to early August, the 15–24 mm tawny brown moth first appears. Eggs are laid in masses on needles in two or three rows that overlap (OMNRF, 2014).

Jack pine budworm range

In the subboreal forests of North America east of the Rocky Mountains, the native insect jack pine budworm *(Choristoneura pinus pinus* Free,) periodically impacts patches of jack pine *(Pinus banksiana* Lamb.) (McCullough, 2000). Jack pine budworm outbreaks typically happen every 6 to 12 years and occur for approximately 2-4 years. The frequency of outbreaks varies and is related to site-specific factors. The quantity of male pollen cones, which offer larvae shelter until current-year needles expand, is correlated with the survival of early-instar larvae during spring dispersal. Defoliated Jack pine trees produce few pollens cones the following year, frequently leading to high early-stage larval mortality. Jack pine budworm is attacked by a wide range of generalist parasites, but only a few species are responsible for most of the mortality in any given region. Jack pine budworm populations that are collapsing exhibit sharp drops in early instar survival as well as an increase in parasitism during the late larval and pupal stages.

Figure 1. Jack pine budworm feeding.

(OMNRF, 2014)

Increased parasitism of late-stage larvae or pupae and low pollen cone production in tandem are consistent with second-order density dependence factors (McCullough, 2000). Numerous jack pine budworm outbreaks have occurred roughly at the same time since the 1950s across a sizable area indicating that Moran effect processes as well as moth dispersal or other factors may be involved in jack pine budworm dynamics. Although most trees can recover due to outbreaks (McCullough, 2000); brief duration, dead and top-killed trees eventually build up in affected jack pine stands. When a fire breaks out, the buildup of dead trees and other woody debris frequently causes intense wildfires. Stand dynamics following JPBW outbreaks: Jack pine, jack pine budworm, and fire work together in a symbiotic relationship that keeps stands healthy and provides jack pine budworm with ongoing hosts (McCullough, 2000). Abiotic factors, such as climate and soils, drive biome and landscape-level patterns of vegetation at the broadest scales; at smaller scales, interactions between abiotic and biotic factors create a mosaic of communities and individuals. Disturbances, such as drought, fire, wind, and insects, play a role at all scales by affecting both abiotic and biotic components, and thus successional processes (Gill, 2014).

The jack pine budworm is a well-adapted insect that is a regular component of the Atlantic Coastal Pine Barrens' natural disturbance cycle located on the Eastern coast of Canada as seen in Figure 2

.

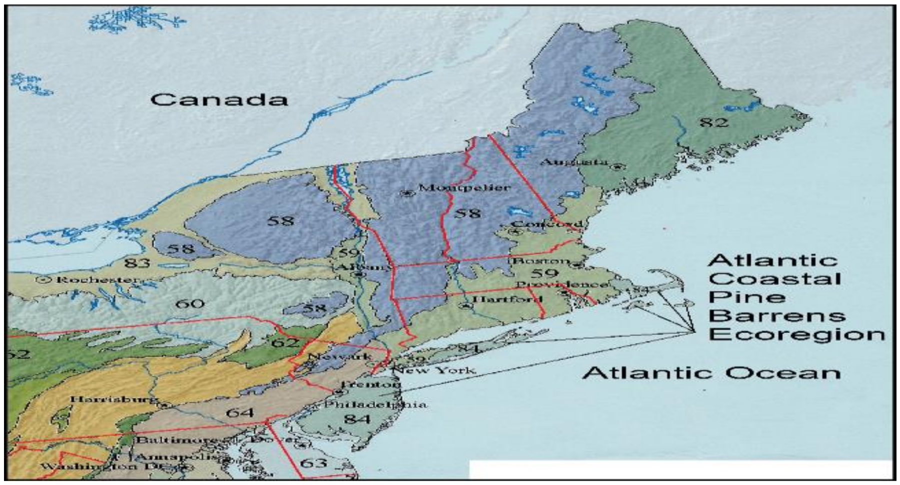


Figure 2. Atlantic Coastal Pine barren.

(Reynolds, 2016)

JPBW and fire

The mortality of jack pine caused by budworms raises the fuel load and the possibility of a stand-replacing fire, which causes jack pine to regenerate more powerfully than its rivals. The productivity of the site has an impact on defoliation rates, and stand composition is another factor to consider (Radeloff, Mladenoff, & Boyce, 1999).

While a study done in Wisconsin revealed defoliation rates were higher in moderate to rich sites, Weber noted that defoliation rates increased in poor sites (Weber, 1995). Stands of pure jack pine might have more defoliation. Likewise with spruce budworm. In the future, defoliation levels could be determined using satellite imagery (Radeloff, Mladenoff, & Boyce, 1999).

Ontario JPBW Observations

Aerial mapping of 346,266 ha of moderate to severe jack pine budworm defoliation was completed in 2021, primarily in the northwest region with a smaller area in the northeast region.

Defoliation has decreased significantly in this area over the last three years. Aerial mapping was difficult and somewhat limited in the northwest region due to safety concerns associated with fires and smoke advisories (Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry, 2022).

Northwest Ontario JPBW Outbreak

The total area of moderate to severe jack pine budworm defoliation in the Thunder Bay District increased from 3,761 ha in 2020 to 107,439 ha in 2021. Most of the total area of moderate to severe jack pine budworm defoliation in the Thunder Bay District increased from 3,761 ha in 2020 to 107,439 ha in 2021. Most of the defoliation was mapped in the district's northern half, from Dawn Lake in Wabakimi Provincial Park in the north to Kopka Lake on the west side of Lake Nipigon in the south, and from the western district boundary by Foam Lake to Falcon Lake by the eastern district boundary as seen in Figure 3.

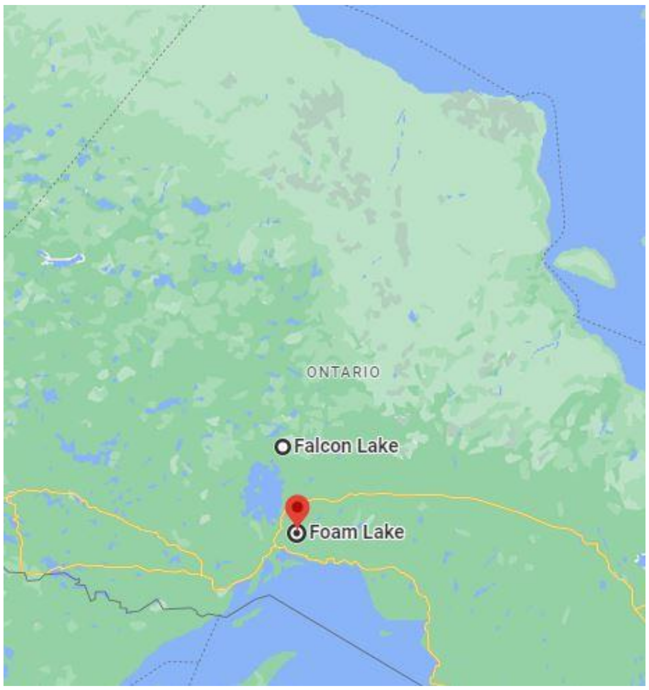


Figure 3. Foam Lake to Falcon Lake JPBW affected area.

The remaining moderate to severe jack pine budworm defoliation was mapped on the district's west central side, west of Upsala. It was concentrated on the north side of Highway 17, from the Graham

Road exit near Hay Lake to Goshen Lake near the district boundary. Along the Firesteel River south of Highway 17 in this same general area, moderate to severe defoliation was also observed. Further west on Highway 17, a large area of defoliation was identified near the Thunder Bay/Dryden district boundary near the English River between Hawk and Savoy lakes. The total area of moderate to severe jack pine budworm defoliation in the Thunder Bay District increased from 3,761 ha in 2020 to 107,439 ha in 2021 (Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry, 2022).

Defoliator Epidemic Effects on Fuels and Wildfire

Defoliators frequently don't kill their hosts, therefore their influence on fuels tends to be subtle and slow. In North America, defoliants' impacts on forest structure and fuels have been debated for a century, although a few empirically based results have been published. As is the case with bark beetles, the influence of defoliators on wildfire occurrence and behaviour relies on how fuel loading, fuel connection, and fuel complexity vary with time following the outbreak (Fettig, et al. 2022). In experimental burns 5–8 years after an eastern spruce budworm epidemic in Ontario, Canada, increased surface fuel loadings altered crowning and wildfire spread (Fettig, et al. 2022). Spring fires that occur before green-up showed the greatest change in fire behaviour in response to defoliation, although summer fire behaviour also changed as mortality increased. In Ontario, vertical fuel quantity and connectivity peaked 16 years post-epidemic (Fettig, et al. 2022). Nine years after defoliation, crown breakage, surface fuels, and ladder fuels all increased (Fettig, et al. 2022). The Canadian Forest Fire Behavior Prediction System formalizes these lagged impacts in fuel type characteristics. These fuel categories are static and don't account for fuel development from epidemic onset to tree mortality and fire risk (Fettig, et al. 2022). Following eastern spruce budworm epidemics, burned area increases after 8–10 years. Similar, latency improves ignition probability and fire severity in the affected forest areas. This is because the spruce budworm outbreaks cause significant damage to the forest canopy, leading to increased fuel loads on the forest floor, which can make the forest more susceptible to fires. A modest decrease in ignition risk has been documented soon after defoliation, presumably due to more understory plants and site-level moisture (Fettig, et al. 2022). Controlling for fire weather revealed these impacts (Fettig, et al. 2022).

Temporal Lags and Fire Cycle

Eastern spruce budworm outbreaks in Ontario are commonly followed by temporal lags in burned area, with high probability of ignition. (Nealis, et al. 2003) However, there is little to no information as to how burnt areas were impacted by either jack pine or western spruce budworm outbreaks. The impact of eastern spruce budworm outbreaks on fuels and wildfires are, subsequently influenced by weather patterns. After an outbreak of the eastern spruce budworm in eastern Canada, lagged defoliation influenced ignition probabilities, but there were no recorded increases in surface fuels or fire hazards. (Nealis, et Al. 2003). This result may have been influenced by the wet weather conditions experienced that, in turn, may have accelerated the breakdown of fuel which occurs when wet conditions are matched with high temperatures and the fuel loadings breakdown at a faster rate. (Nealis, et Al. 2003). Within Ontario's previously identified window of opportunity which refers to a period when a forest is more susceptible to disturbances such as defoliation by insects and subsequent wildfires (Nealis, et al. 2003), defoliation-fire occurrences have been more frequent and tend to vary spatially according to host availability and temperature (Nealis, et al. 2003). Outbreaks of the western spruce budworm have been shown to modify the fuel composition and fire behaviour but not the intensity. In general, epidemics of western spruce budworm seem to have reduced the frequency of fires. This reduction in wildfire frequency, however, has not been observed during outbreaks of the eastern spruce budworm, which may draw attention to the depletion of fuel load changes during an outbreak and the essential differences between defoliator systems.

Ring Response and Wood Quality

In central Canada, the tree-ring responses of jack pine and Scots pine to budworm defoliation have been investigated. According to the study, budworm defoliation reduced growth in both jack pine and Scots pine, which demonstrated a negative correlation between ring width and defoliation. Between the two species, there were differences in the strength of the reaction, with jack pine responding more strongly than Scots pine. The impacts of budworm defoliation on forest ecosystems can be studied using tree-ring analysis (Robson, et al. 2015).

JPBW outbreaks cause a tree-ring with thin latewood in the first year. Radial growth suppression produces narrow rings until the host tree begins to recover. Due to stored reserves being used to compensate for reduced photosynthesis, radial growth may be delayed by one to two years after defoliation. Top-killed trees may experience more extended growth suppression and host-tree decline. Light rings (i.e., tree growth rings that have fewer latewood tracheids and thinner cell walls) were associated with declining jack pine trees after severe JPBW (Robson, et al. 2015).

Although jack pine is an important commercial species, there have been very few studies that have examined the host species' tree-ring response to JPBW defoliation. to calibrate long-term JPBW outbreak records with host species radial growth suppressions. Tree-ring records could improve dendroclimatic reconstruction signal-to-noise ratios and long-term JPBW population dynamics (Robson, et al. 2015). Tree rings records can predict outbreaks by providing high-resolution data on past climate variability and insect outbreak events. By analyzing the width and density of tree rings, researchers can reconstruct past environmental conditions and infer the impact of insect outbreaks on tree growth. This information can be used to improve our understanding of the relationships between climate variability, insect outbreaks, and forest dynamics over long timescales Signal-to-noise ratio (SNR) is the ratio of noise in tree-ring data. Tree-ring data records past climate in yearly growth rings. Tree growth and environmental factors like weather, precipitation, and soil moisture, and in this case insect impacts. Historical documents on JPBW outbreaks and plantation management in Spruce Wood Provincial Forest (SWPF) led to four objectives (Robson, et al. 2015). The first goal was to find outbreak-associated tree-ring signatures in both host species. JPBW defoliation sensitivity was the second objective. The third and fourth objectives examined how management operations and climate variables affected JPBW outbreak dynamics (Robson, et al. 2015).

METHODS AND MATERIALS

Study Site Description

Ten mature, fire-origin mature (>80 years) jack pine-dominated (>80%) stands were selected for this study. Five of the stands were in an area affected (moderate to severe defoliation) by the current, ON, while the other five were in unaffected stands east of Ignace, ON (Figure 4). All stands were established on glaciofluvial deposits with coarse textured sediments (medium to fine sands).

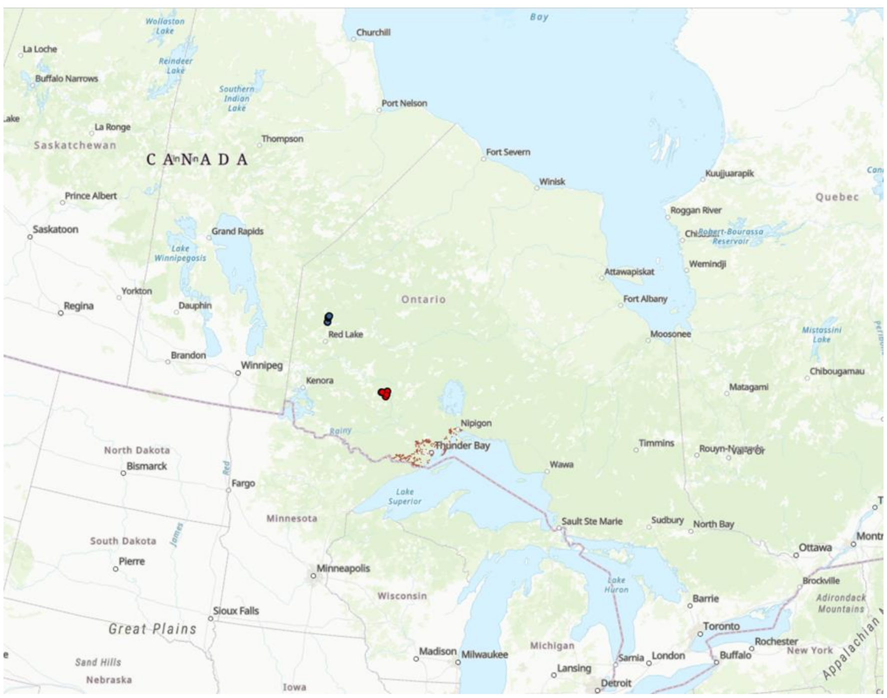


Figure 4 Map of study plot locations: control plots (red) and JPBW plots (green)

The control plot that are indicated by the red dots are in the 3W (Figure 5) ecoregion of Ontario (OMNR, 2022). The ecoregion's alpine flora includes black and white spruce, balsam fir, trembling aspen, white birch, and jack pine. White spruce and balsam fir grow well on Lake Nipigon's good substrates.

Large jack pine and jack pine-black spruce conifer woods dominate the western ecoregion around Ignace, Graham, and Raith. The 3W region's soil structure is typically well-drained, coarse-textured substrates. Neutral to calcareous, fine-textured soils have patterns indictive to permafrost soils (OMNR, 2022).

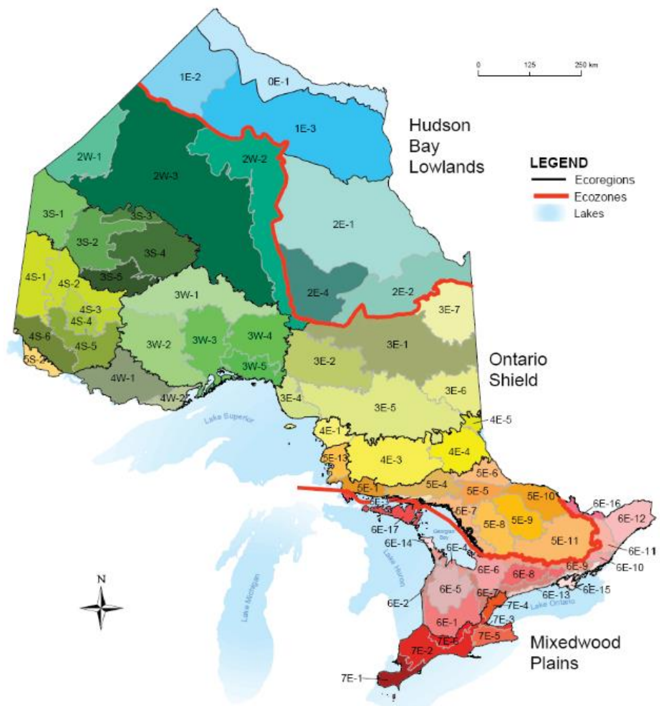


Figure 5 Ecoregions of Ontario

(OMNR, 2022)

The JPBW plots were located north of Red Lake as seen in Figure 4 which is categorized as the 3S ecoregion in Ontario (OMNR, 2022). The species composition of this area is generally White Birch (*Betula papyrifera* Marshall), Trembling aspen (*Populus tremuloides* Michx.), that grow along with black spruce and jack pine in pure or mixed stands. Large wide peatlands typically predominate in lowlands (fens or bogs). Lowland forests are primarily made up of black spruce and tamarack. Balsam poplar and black ash are found in lowland and riparian mixed wood woods on richer, moister mineral sites. (With pockets of glaciolacustrine clays in lower topographic locations, the ecoregion is a moderately sloping plain of relatively shallow sandy and loamy tills over bedrock, broken at irregular intervals by esker and moraine ridges (OMNR, 2022). Organic deposits can be found in poorly draining regions, and 13% of the land is made up of exposed bedrock. The south is elevated and rocky. The substrate stratum is composed of granitic coarse and medium sands, loams, and low-base sands. The carbonate concentration in this region was increased northeastward by the last glaciation, which brought materials from the Hudson Bay Lowlands Ecozone. These soils have layering patterns brought on by permafrost, just like the 3W area (OMNR, 2022).

Field Measurements

In 2019, five circular, fixed area permanent growth plots (400 m^2) were randomly established at each study site (total of 50 PGPs) that were a minimum of 50 m apart from each other. However, some plots in the control area were reduced to 200 m^2 plots due to a workload issue resulting from high densities. Within the plot boundaries, all trees with a diameter greater than 2.0 cm had their species, status (alive or dead), and dbh recorded. Total height and an ocular estimate of crown density were also recorded on 25% of the live trees in each plot. Ocular height and decay class of all standing dead trees were also recorded. Repeat measures have been done annually since establishment (2019-2022), with a complete census of crown density for live jack pine trees in 2022 to evaluate tree recovery from the budworm outbreak.

Data Synthesis and Analysis

The measured height – Dbh data pairs were used to develop height – Dbh regression equations, by tree species using a 2-parameter power function to generate modelled heights for the complete dataset.

$$Ht(pred) = 1.3 + b_1 * \left(Dbh^{b^2}\right)$$

Where Ht(pred) is the predicted height (m), and Dbh is the diameter at breast height (cm). The derived model coefficients are $b_1$and b_2, with the y-intercept set at 1.3 (Dbh = 0). These curvilinear equations were generated using Proc NLIN in SAS Version 9.1 (see Appendix 1). These equations were applied to all of the remaining trees that did not have height measurements done on them, to follow up with the calculation of individual tree volumes.

To predict individual stem volume for all trees, Horner's species-specific equations, updated to metric units, were then used (Horner, 1967).

$$v_{Tot}(M) = \frac{a^2(d1.3)^2}{a^0 + \frac{a^1}{Hm}}$$

where: $V_{Tot\,(M)}$is the Gross Total Volume (GTV) of the individual stem (m^3), d 1.3 is the measured Dbh (cm), and Hm is the measured/ modelled total height (m). In this equation a^0, a^1, a^2 represent the metric derived model coefficients (Table 1).

Table 1. Metric- derived model coefficients for Honer's stem volume equation for the five species recorded in the PGPs

Species	metric derived coefficients		
	a_0	a_1	a_2
White Pine	0.691	110.848	0.004319
Red Pine	0.710	108.394	0.004331
Jack Pine	0.897	106.232	0.004331
Black Spruce	1.588	101.609	0.004327
Red Spruce	1.226	96.266	0.004325
White Spruce	1.440	104.295	0.004322
Balsam Fir	2.139	91.938	0.004331
Cedar	4.167	74.647	0.004330
Hemlock	1.112	106.708	0.004330
Trembling Aspen	-0.312	133.101	0.004341
Balsam Poplar	0.420	120.287	0.004341
White Birch	2.222	91.554	0.004322
Yellow Birch	1.449	105.081	0.004320
Maple	1.046	117.035	0.004334
Basswood	0.948	122.364	0.004334
Beech	0.959	102.056	0.004334
Black Cherry	0.033	119.889	0.004334
White Elm	0.634	134.263	0.004334
Ironwood	1.877	101.372	0.004334
Red Oak	1.512	102.568	0.004334

From the recorded plot data, stand-level metrics (e.g., species composition, density – live and standing dead, and gross total volume – live and standing dead) were calculated and converted to a "per hectare" basis. Temporal trends (2019-2022) were examined comparing the JPBW affected stands to the unaffected stands.

The plot-level data was subjected to a 2-way ANOVA with time-since-infestation (sampling year) and stand condition (JPBW affected versus non-affected stands) treated as main effects. The individual plots within the individual sites were treated as sampling units and the individual sites within the stand condition as experimental units. Proc GLM in SAS/STAT (version 9.4) was used to perform the analysis, and the student-Newman-Keuls (SNK) post-hoc means separation test was used to examine significant effects ($p<0.05$) between levels within each main factor.

RESULTS

In terms of jack pine live tree density (stems ha^{-1}), the budworm-affected stands did initially (2019 assessment) have higher (p 0.0409) densities than the unaffected stands but declined in 2020 and were similar to the unaffected stands out to 2023, possibly the result of having greater densities prior to the budworm outbreak (Figure 6).

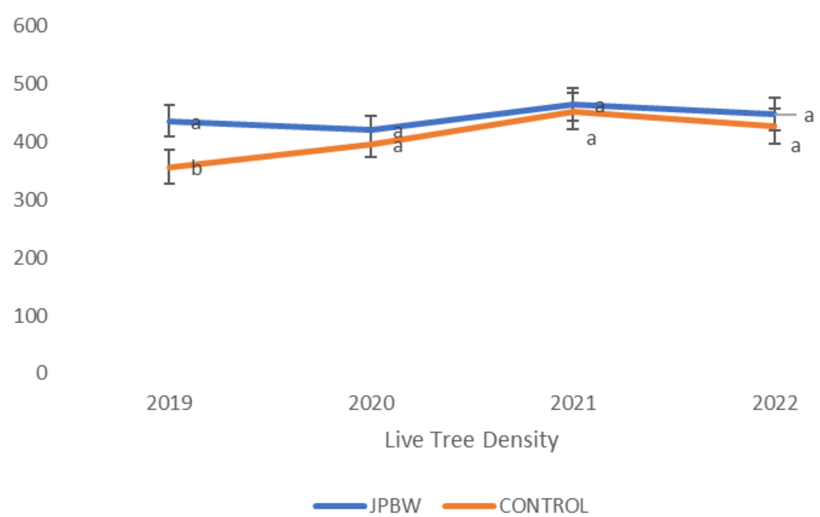


Figure 6 Temporal trends in live jack pine tree density for jack pine affected versus unaffected stands. Vertical bars represent standard errors. Different lowercase letters represent significant ($p<0.05$) differences between treatments, based on the SNK post- hoc means separation test.

In contrast, standing dead tree densities were significantly higher (p 0.0018) in the budworm affected stands when compared to the unaffected stands, and did increase over the four sampling years (Figure 7).

It is worth noting, however, that the unaffected controls sites also had increasing standing dead densities over time as a function of natural self-thinning processes.

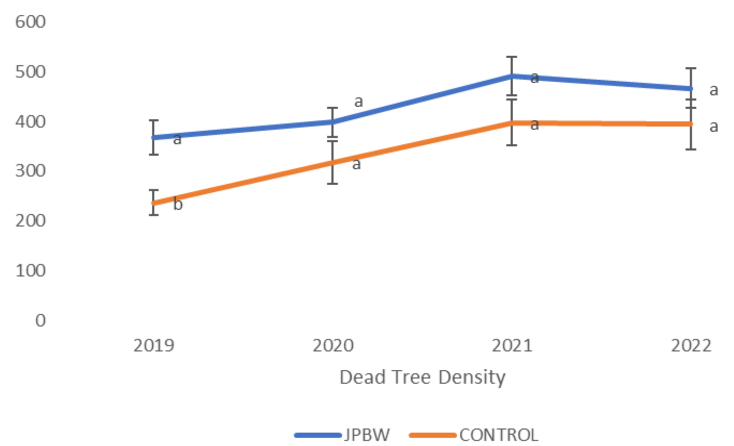


Figure 7. Temporal trends in dead tree density for jack pine affected versus unaffected stands. Vertical bars represent standard errors. Different lowercase letters represent significant (p<0.05) differences between treatments, based on the SNK post- hoc means separation test

.

Figure 8 Temporal changes in live tree crown density (% fullness) of jack pine trees affected by JPBW versus unaffected (control) stands. Vertical bars represent standard errors. Different lowercase letters represent significant (p<0.05) differences between trees

The crown density (i.e., ocular estimate of the percentage of foliar mass within the live crown) in budworm affected stands was significantly lower ($p<0.0001$), generally 5-10% lower in budworm affected stands compared to unaffected stands, but the remaining live trees appear to be recovering to nearly the same value as those in the unaffected stands by 2022 (Figure 8).

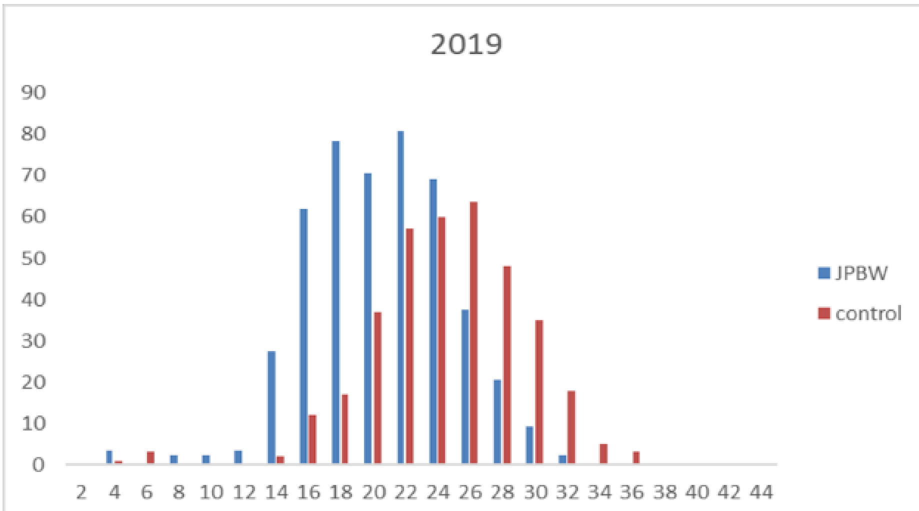


Figure 9 Live tree diameter distribution in 2019 for JPBW affected versus unaffected (control) stands (stems ha-1, by 2cm diameter classes).

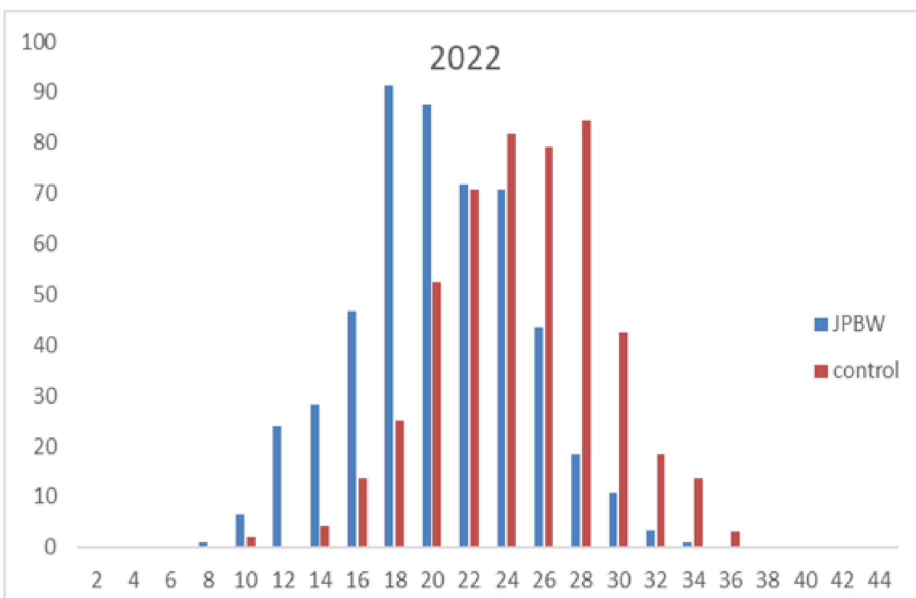


Figure 10. Live tree diameter distribution in 2019 for JPBW affected versus unaffected (control) stands (stems ha-1, by 2cm diameter classes)

From 2019 (Figure 9) to 2022 (Figure 10), the diameter distribution is showing the loss of the larger more dominant trees in the JPBW affected stands and has resulted in greater densities of smaller trees (mid-canopy). The loss of some dominant canopy pine has given the mid-canopy trees more light, thereby preventing them from dying as a result of competition or self-thinning processes. This has resulted in a loss of annual stand volume of about $57 m^3 ha^{-1} yr^{-1}$. The annual loss of volume is showing signs of decreasing over time, with only 27.4 $m^{3v} ha^{-1} yr^{-1}$.

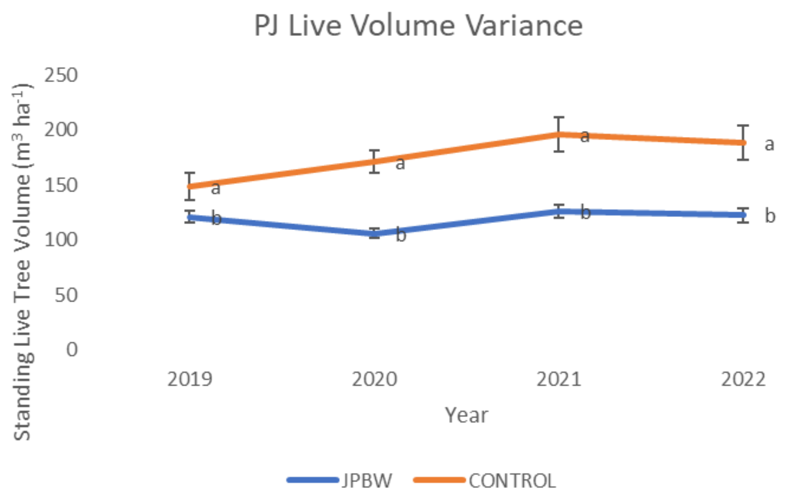


Figure 11 Temporal changes in jack pine live tree volumes in JPBW affected versus unaffected (control) stands. Vertical bars represent standard errors. Different lowercase letters represent significant ($p<0.05$) differences between treatments, based on the SNK post hoc means separation test

Jack pine budworm-infested stands had significantly changed (p 0.0490) in live tree volumes compared to the control stands (Figure 11). Both stand types did, however, have similar dead tree volumes ($p=0.083$) (Figure 12).

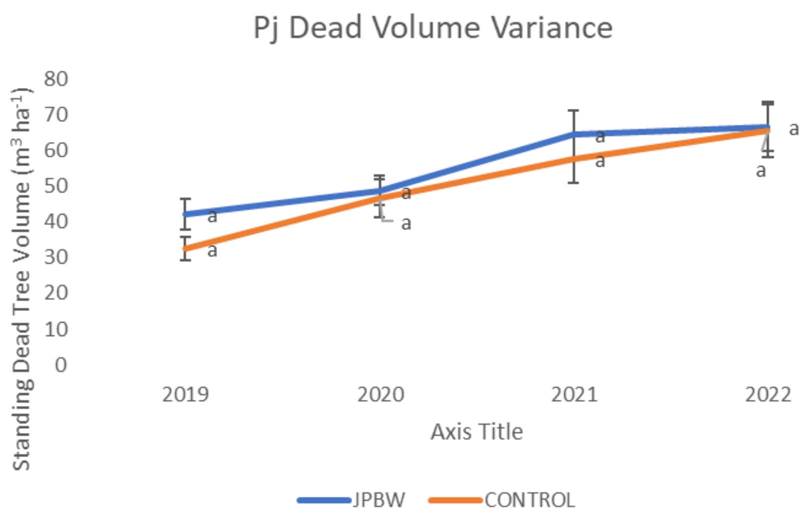


Figure 12 Temporal changes in jack pine live tree volumes in JPBW affected versus unaffected (control) stands. Vertical bars represent standard errors. Different lowercase letters represent significant ($p<0.05$) differences between treatments, based on the SNK post hoc means separation test.

DISCUSSION

-In Ontario, jack pine budworm outbreaks are cyclical, occurring every 10-15 years. Significant defoliation and mortality occurs in stands dominated by jack pine. It is crucial to observe and track stand-level responses like mortality and recovery because these outbreaks have been known to have significant ecological and economic effects. By doing this, we can create sensible management plans and gain a greater understanding of how budworm outbreaks affect these ecosystems. Since this study focused on 3W and the 3S ecoregion it could be pertinent to study outbreaks with higher tree density or areas with a different stand or soil structure to see how the impacts vary across broader landscape regions. JPBW appears to prefer low nutrient stands, but the impact in mid- to high-nutrient stands has not been well documented.

Regular forest inventory and forest health monitoring are important approaches to evaluate the stand-level effects of JPBW infestations. This entails monitoring tree death rates and evaluating the stand's regrowth. Permanent plots can be used to monitor mortality rates, and seedling surveys can be used to evaluate regeneration. We can better comprehend the effects of budworm outbreaks on jack pine stands and create effective management strategies by analysing the data obtained from these methods. Monitoring age class and diameter of tree impact by JPBW can be helpful since studies mentioned have indicated young trees are at higher risk. The results also conclude that the smaller, mid-canopy trees in the JPBW affected stands had lower competition-induced mortality due to mortality of dominant canopy trees.

One management technique that can be used to lessen the effects of budworm outbreaks on subsequent wildfire is commercial thinning. By doing “quality” (i.e., removing recently killed or low vigour trees that are likely to die) commercial thinning in affected areas the potential of future fuel loading would be decreased. Prescribed burns may also be affective technique to reduce post-budworm fuel loadings and may be beneficial in reducing the intensity or severity of insect infestations (Mccullough & Kulman, 1991). Prescribed fires, however, may not always be effective in managing pest infestations and may even exacerbate the situation if not used correctly. If a prescribed burn is carried out during the peak of a budworm outbreak, it may eliminate the budworms' natural predators and rivals, leading to an increase in their numbers.

In order to decrease the quantity of fuel available for fires to spread, thinning widens the space between trees. This makes it simpler for firefighters to put out wildfires in the affected regions by establishing a natural firebreak. Furthermore, thinning can improve the strength and resistance of the remaining trees, enabling them to more effectively endure budworm outbreaks in the future. With the use of tree ring analysis further historical tracking of JPBW can be used to monitoring changing trends in a larger amount of time.

Another strategy is to make use of modelling in order to anticipate non-linear outbreaks. It is possible for budworm populations to experience non-linear epidemics when they pass a critical threshold and begin to rapidly expand throughout the forest. By modelling these outbreaks, we can gain a better understanding of the conditions that lead to the emergence of non-linear epidemics and develop preventative management strategies to mitigate the damage caused by them. These models can take into consideration a wide range of factors, including the number of trees in an area, the size of the budworm population, and the weather conditions, in order to make accurate predictions regarding when an epidemic is likely to occur. Since climate change is progressing, the cyclical outbreaks of JPBW are becoming nonlinear and can be correlated to changing forest conditions such as moisture, temperature changes, and break down of fuel loadings. With these indicators in mind, managers can further their knowledge and gain insight into changing insect outbreaks

CONCLUSION

It is valuable to track stand-level responses, such as mortality and recovery, in jack pine-dominated stands following jack pine budworm outbreaks in Ontario to improve our understanding the extended effects of these outbreaks on ecosystem structure and function. Through regular monitoring and inventory, we can develop effective management strategies such as commercial thinning to minimize the longer-term effects of these outbreaks on forest structure, fuel loadings, and wildfire threats to northern communities. By analyzing the data collected from these permanent plots, we can better understand the response of the ecosystem to budworm outbreaks and make informed decisions to manage and mitigate their impact.

Results support the management option of commercial thinning in budworm affected stands that may help to reduce the impact of budworm outbreaks by reducing fuel loadings, provide input to local wood supplies, and increase the vigor and resistance of the remaining trees. Additionally, future sampling can help managers predict non-linear outbreaks and develop proactive management strategies to prevent or minimize their impact with tree ring analysis, density sampling, and silviculture management.

Overall, managing budworm outbreaks is crucial for maintaining the ecological and economic health of Ontario's forests. By tracking stand-level responses and implementing effective management strategies, we can help preserve these valuable ecosystems and ensure their sustainability for future generations.

LITERATURE CITED

References

Desponts, M., & Payette, S. (1991). Recent dynamics of jack pine at its northern distribution limit in northern Quebec . *Centre d'e'tudes tzordiques*.

Farrar, J. (2017). *Trees in Canada.* Fitzhenry & Whiteside .

Fettig, C., Runyon, J., Homicz, C., James, P., & Ulyshen, M. (2022). *Fire and Insect Interactions in North American Forests.* FIRE SCIENCE AND MANAGEMENT.

Gill, K. (2014). Structure, dynamics, and climate sensitivity of range-margin jack pine forests in . *UNIVERSITY OF MINNESOTA*.

Google Earth. (2023). *Google Maps*.

Horner, W. G. (1967). *Standard volume tables and merchantable conversion factors for the commercial tree species of central and eastern Canada.* Canadian Department of Forestry and Rural Development .

James, P., Robert, L., Wotton, E., Martell, D., & Fleming, R. (2017). *Lagged cumulative spruce budworm defoliation affects the risk of fire ignition in Ontario.* Ecological Applications.

McCullough, D. (2000). *A review of factors affecting the population dynamics of jack pine budworm (Choristoneura pinus pinus Freeman).* Population Ecology.

Mccullough, D., & Kulman, H. (1991). Differences in foliage quality of young jack pine (Pinus banksiana Lamb.) on burned and clearcut sites:effects on jack pine budworm (Choristoneura pinus pinus Freeman). *Department of Entomology*.

Nealis, V. G., Magnussen, S., & Hopkin, A. A. (2003). *A lagged, density-dependent relationship between jack pine budworm Choristoneura pinus pinus and its host tree Pinus banksiana.*

OMNR. (2022, Novermber 22). *The ecosystems of Ontario – Part 1: ecozones and ecoregions*. Retrieved from Environment and energy: https://www.ontario.ca/page/ecosystems-ontario-part-1-ecozones-and-ecoregions

OMNRF. (2014, July 18). *Jack pine budworm*. Retrieved from Ontario Ministry of Natural Resources: https://www.ontario.ca/page/jack-pine-budworm

Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry. (2022). *Forest Health Conditions in Ontario 2021.* Queen's Printer for Ontario.

Radeloff, V., Mladenoff, D., & Boyce, M. (1999). Detecting Jack Pine Budworm Defoliation Using Spectral Mixture Analysis: Separating Effects from Determinants. *Remote Sensing of Environment*.

Reynolds, J. W. (2016). *The Atlantic Coastal Pine Barrens Ecoregion in the United States.* ResearchGate.

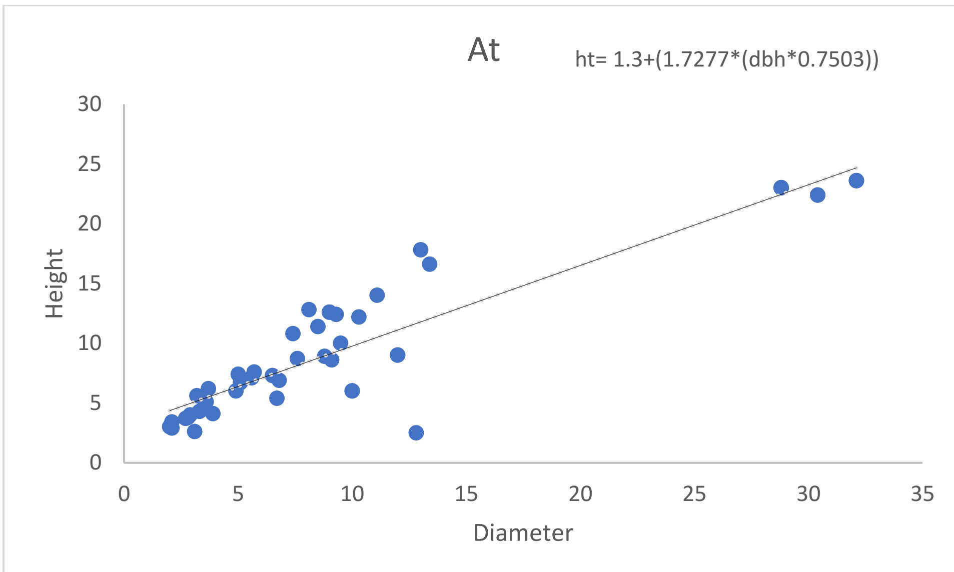
Robson, J. M., Conciatori, F., Tardiff, J. C., & Know, K. (2015). *Tree-ring response of jack pine and scots pine to budworm defoliation in central Canada.* Elsevier B.V.

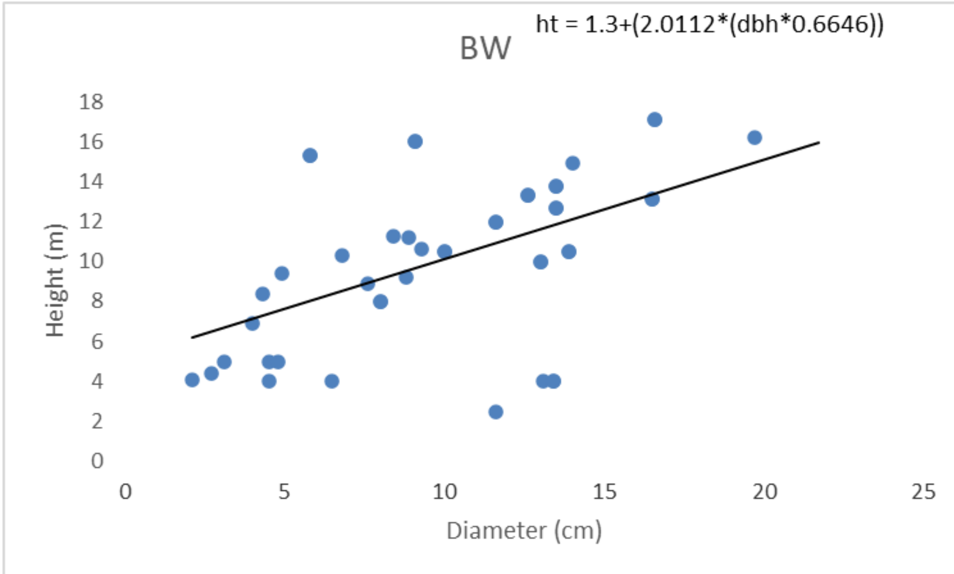
Weber, S. (1995). *Integrating budworm into jack pine silviculture in northwest Wisconsin.*

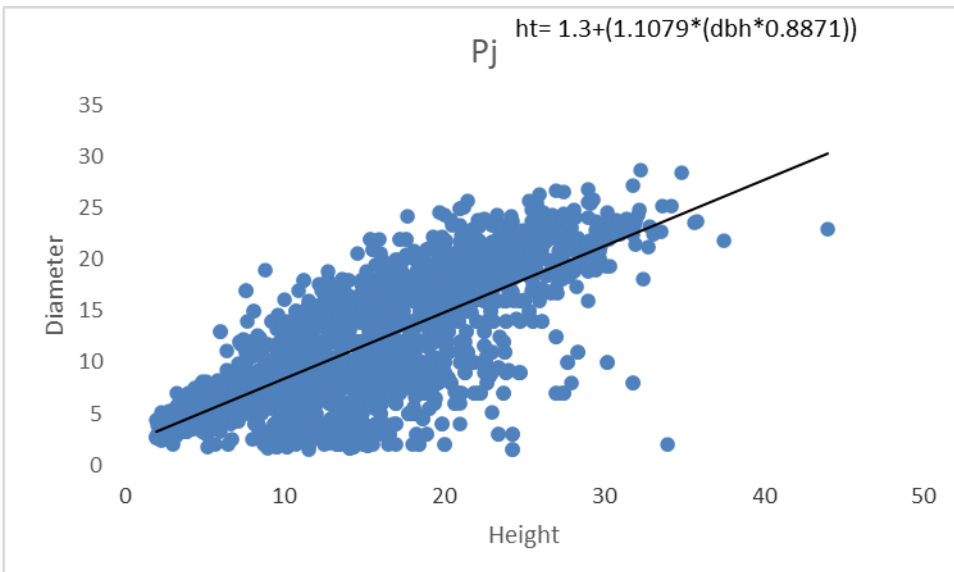
APPENDICES

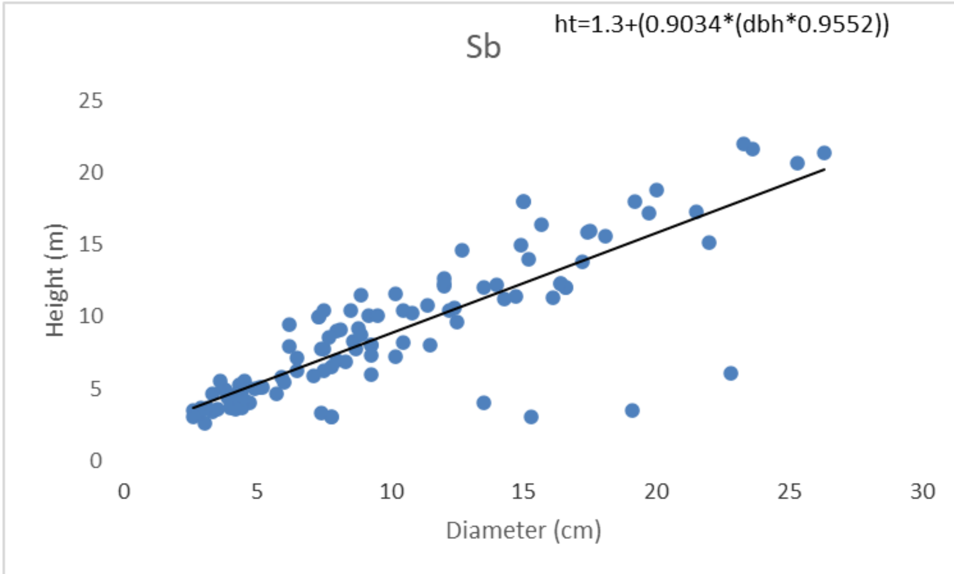
APPENDIX I

The relationship for height and diameter was graphed for Trembling Aspen (*Populus tremuloides*), Balsam Fir *(Abies balsamea)*, *(Betula papyrifera)*, Jack Pine, and Black Spruce *(Picea mariana)*.




ht = 1.3+(2.0112*(dbh*0.6646))
BW
Height (m)
0 2 4 6 8 10 12 14 16 18
0 5 10 15 20 25
Diameter (cm)


ht= 1.3+(1.1079*(dbh*0.8871))
Pj
Diameter
0 5 10 15 20 25 30 35
0 10 20 30 40 50
Height


ht=1.3+(0.9034*(dbh*0.9552))
Sb
25
20
15
10
5
0
Height (m)
0
5
10
15
20
25
30
Diameter (cm)

APPENDIX II

Live jack pine density ANOVA

The SAS System 10:10 Thursday, March 2, 2023 17

--- Year=2019 ---

The GLM Procedure

Class Level Information

Class	Levels	Values
SType	2	JPBW control

Number of Observations Read	50
Number of Observations Used	50

The SAS System 10:10 Thursday, March 2, 2023 18

--- Year=2019 ---

The GLM Procedure

Dependent Variable: svolha

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	9397.6194	9397.6194	4.08	0.0490
Error	48	110523.3050	2302.5689		
Corrected Total	49	119920.9244			

R-Square	Coeff Var	Root MSE	svolha Mean
0.078365	35.58619	47.98509	134.8419

Source	DF	Type I SS	Mean Square	F Value	Pr > F
SType	1	9397.619386	9397.619386	4.08	0.0490

Source	DF	Type III SS	Mean Square	F Value	Pr > F
SType	1	9397.619386	9397.619386	4.08	0.0490

The SAS System 10:10 Thursday, March 2, 2023 19

--- Year=2020 ---

The GLM Procedure

Dependent Variable: svolha

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	50617.6500	50617.6500	31.61	<.0001
Error	46	73670.6425	1601.5357		
Corrected Total	47	124288.2925			

APPENDIX III
Dead jack pine density ANOVA

-- Year=2019 ---

The GLM Procedure

Dependent Variable: deadden

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	252050.000	252050.000	10.98	0.0018
Error	48	1102250.000	22963.542		
Corrected Total	49	1354300.000			

R-Square	Coeff Var	Root MSE	deadden Mean
0.186111	49.20041	151.5373	308.0000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
SType	1	252050.0000	252050.0000	10.98	0.0018

Source	DF	Type III SS	Mean Square	F Value	Pr > F
SType	1	252050.0000	252050.0000	10.98	0.0018

The SAS System 10:10 Thursday, March 2, 2023 96

-- Year=2020 ---

The GLM Procedure

Dependent Variable: deadden

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	84875.362	84875.362	2.51	0.1197
Error	46	1553041.304	33761.767		
Corrected Total	47	1637916.667			

R-Square	Coeff Var	Root MSE	deadden Mean
0.051819	51.27733	183.7438	358.3333

Source	DF	Type I SS	Mean Square	F Value	Pr > F
SType	1	84875.36232	84875.36232	2.51	0.1197

Source	DF	Type III SS	Mean Square	F Value	Pr > F
SType	1	84875.36232	84875.36232	2.51	0.1197

The SAS System 10:10 Thursday, March 2, 2023 99

-- Year=2021 ---

APPENDIX IV
Crown density ANOVA results

```
----------------------------------------- Year=2019 ------------------------------------------

                         The GLM Procedure

Dependent Variable: CDensity   CDensity

                              Sum of
   Source              DF        Squares     Mean Square    F Value    Pr > F

   Model                1     150036.9997     150036.9997     469.89    <.0001

   Error              303      96749.5577        319.3055

   Corrected Total    304     246786.5574

            R-Square     Coeff Var      Root MSE    CDensity Mean

            0.607963      26.18343      17.86912         68.24590

   Source              DF       Type I SS     Mean Square    F Value    Pr > F

   SType                1     150036.9997     150036.9997     469.89    <.0001

   Source              DF     Type III SS     Mean Square    F Value    Pr > F

   SType                1     150036.9997     150036.9997     469.89    <.0001
                          The SAS System       10:10 Thursday, March 2, 2023  33
----------------------------------------- Year=2020 ------------------------------------------

                         The GLM Procedure

Dependent Variable: CDensity   CDensity

                              Sum of
   Source              DF        Squares     Mean Square    F Value    Pr > F

   Model                1      59942.1219      59942.1219     122.93    <.0001

   Error              786     383258.4809        487.6062

   Corrected Total    787     443200.6028

            R-Square     Coeff Var      Root MSE    CDensity Mean

            0.135248      39.72255      22.08181         55.59010

   Source              DF       Type I SS     Mean Square    F Value    Pr > F

   SType                1     59942.12194     59942.12194     122.93    <.0001

   Source              DF     Type III SS     Mean Square    F Value    Pr > F

   SType                1     59942.12194     59942.12194     122.93    <.0001
                          The SAS System       10:10 Thursday, March 2, 2023  36
----------------------------------------- Year=2021 ------------------------------------------
```