DETERMINING GENETIC RESISTANCE TO JACK PINE BUDWORM DEFOLIATION IN JACK PINE FROM DIFFERENT GEOGRAPHIC SEED SOURCES ACROSS ONTARIO

by

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A CAUTION TO THE READER

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Abstract

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Key words: jack pine budworm, defoliation, climate change, assisted migration, seed source.

Jack pine budworm is an outbreak insect that defoliates jack pine forests across Canada. While it is a native species, the outbreaks can have severe economic impacts, such as loss of timber volume and increased risk of severe forest fires, and may also require expensive spray programs to keep the budworm in check. With the climate warming at a rapid rate, it is expected that the cycle of forest disturbances may increase drastically, therefore increasing the duration and severity of outbreaks and decreasing the time between jack pine budworm outbreaks. In this study, I analyzed the defoliation patterns in a jack pine provenance trial in the Red Lake area in northwestern Ontario which had recently been the victim of the start of a jack pine budworm outbreak. The original trial was created in order to see how well certain seed sources would do under the current rapidly changing climatic conditions. Sources from north-western, central, and southern Ontario were used in the original provenance trial. In my study, I compared defoliation severity between the three source locations. I found that seed sources from the north tolerated jack pine budworm defoliation significantly better than both the central and southern sources, and that seed sources from central Ontario performed better than the south as well. The results of this study imply that forest managers should proceed very cautiously when attempting to start an assisted migration program in hopes to negate the effects of climate change. While it may seem like a good idea to get ahead of the rising temperatures, planting foreign seed sources may have devastating unintended consequences.

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INTRODUCTION

There are many species of outbreak insects that, when the conditions are right, are able to cause severe damage to the forests of Canada (Nealis 2003). A well-known example of this is the spruce budworm, which primarily attacks older balsam fir (*Abies balsamaea* (L.)), while also occasionally attacking white spruce (*Picea glauca* (Moench)), and black spruce (*P. mariana* (Mill.)) as well (Freeman 1953). However, there is a very close relative of the spruce budworm called the jack pine budworm (*Choristoneura pinus* Freeman), which, as its name suggests, attacks jack pine (*Pinus banksiana* Lamb.). Unlike the spruce budworm, there is very little known about the jack pine budworm. The jack pine budworm occurs most commonly as an outbreak species in northern Ontario and into the boreal forests in western Canada throughout the prairies. It will defoliate jack pine trees by eating the current years' foliage, and, if necessary, pollen cones.

Historically, jack pine budworm outbreaks haven't been very severe or economically damaging (Freeman 1953), but with climate change occurring at a rapid rate, these outbreaks have persisted longer (Nealis 2016), resulting in greater damage to jack pine forests of northern Ontario. With these outbreaks occurring approximately every 8-10 years in Ontario and lasting for 4 years, a large proportion of a jack pine forest's life will be spent vulnerable to attack from the jack pine budworm, resulting in not only high timber volume losses, but also an increase in forest fire hazards, which will put camp owners, tourists, and even entire communities at risk. The economic effects may also become detrimental to communities and businesses, as jack pine is one of the most important species in northern Ontario forestry. As a result, learning more about the jack pine budworm is going to become crucial for forest management in the future, and it would be better to understand this species sooner rather than later so that when the jack pine budworm becomes a serious forest threat, we will be already prepared to defend our forests.

In my study, I wanted to look at jack pine in an area that was infested with the jack pine budworm and analyze jack pine resistance to the budworm by measuring defoliation levels. My study took place near Red Lake, Ontario, on the Trout Forest SFL. The study was conducted on Dr. William Parker's Portfolio Theory (Parker and Crowe 2007) jack pine plantation on Cooley Lake Road. Dr. Parker's test had initially been set up to see how jack pine from 8 various seed sources would grow under the same climatic conditions.

The overall research question I aimed to answer was: Is there genetic resistance to the jack pine budworm between the different Ontario seed sources? My objective was to examine the interaction between jack pine seed source and jack pine budworm defoliation severity, which would ideally provide insight as to what seed source should be planted in northwestern Ontario order to best prevent economic loss due to jack pine budworm defoliation.

My hypothesis is that the seed sources from northern Ontario would display a stronger resistance to the jack pine budworm defoliation when compared with seed sources from central and southern Ontario.

LITERATURE REVIEW

JACK PINE ECOLOGY

Jack pine (*Pinus banksiana* Lamb.) trees have a lifespan of about 80-100 years and is very shade intolerant (MSU 2014). Due to its fire-adapted "serotinous" cones and fuel increasing branches, the jack pine is a very fire adapted species, requiring stand replacing fires to regenerate properly (MSU 2014). However, they are generally a very resilient tree, being able to withstand poor, dry site conditions without being too vulnerable to a lot of severe pests or pathogens (MSU 2014).

A study that aimed to look at the effects that climate change will have on jack pine was conducted by W. Parker and K. Crowe in northwestern Ontario (Parker and Crowe 2007). This study was conducted at three locations in the area, where jack pine seedlings from 8 different geographical areas in Ontario with greatly varying latitudes were planted (Parker and Crowe 2007). One aspect of the study was to see if it would be wise to plant southern seed sources further north so that when the average temperature increases due to climate change, the present trees are already adapted (Parker and Crowe 2007). The objectives of this study go together well with the personal objectives of my study, as both analyzed the ability of jack pine from different locations to tolerate northern Ontario conditions. While the Parker and Crowe (2007) study was conducted over the span of only a few years, it was easy to see that the local seed sources were still doing much better than the most southernly sources (D. Caron, pers. obs. 2019). The most southernly sources ranked lowest in height growth and survival, while local (northern) sources ranked best in survival and second in height growth (Parker and Crowe 2007). While lower height growth could probably be tolerated for at least one generation, a low survival rate of seedings would render planting a southern seed source untenable, as there would be no regenerating trees left when the climate finally does become ideal for the southern seed sources (Parker and Crowe 2007).

While it may not be apparent, there is a difference in jack pine budworm's ability to flourish between previously clear-cut sites and previously burned sites (McCullough and Kulman 1991). Nitrogen, monoterpenes, moisture level, and xylem potential of foliage are all considered to be important factors in growth and development of jack pine budworm. It was determined that nitrogen levels, monoterpenes, needle weight and moisture were higher on the clear-cut sites, which directly corresponded with budworm larvae survival. Budworm larvae have lower survival on fire burned sites, showing that the natural forest processes are actually better for controlling budworm populations than human-caused disturbances (McCullough and Kulman 1991). This is an important implication for the forest industry, but could also be one that simply cannot be dealt with, as it is impossible to just stop harvesting without any economic and ecological consequences.

ECOLOGY/BIOLOGY OF THE JACK PINE BUDWORM (*Choristoneura pinus)*

An article about the comparative ecology of conifer-feeding spruce budworms describes the ecology of a number *Choristoneura* species, one of which is the jack pine budworm (Nealis 2016). Nealis (2016) describes some simple ecological characteristics about the various *Choristoneura* species that are found across Canada, focusing mainly on the varieties of spruce budworm, but also some useful information about the jack pine budworm. Nealis describes the range of the jack pine budworm (hereafter JPBW) to be from north-eastern Alberta in the west of its range, through southern Quebec and into the southern maritime provinces at the far east of its range. The primary host of the JPBW is jack pine, however it utilizes red pine (*Pinus resinosa* Sol. Ex Aiton) as a secondary host.

The article also describes the population dynamics and cyclic style of the JPBW outbreaks (Nealis 2016). In Ontario, the time between outbreaks can be anywhere from 12-17 years, with the average being 15 years. However, throughout much of its range in the rest of Canada, average duration between outbreaks is closer to 10 years. The duration of the actual outbreak however ranges from 2-6 years across Canada and is dependent on location. Potential reproductive rates and lifetime fecundity are also discussed, with one female jack pine budworm laying around 60 eggs per year, with mean fecundity's are about 130 eggs per female.

Understanding the predators and parasites of JPBW are key in learning how to properly defend against outbreaks. Brandt and Melvin (1970) studied the parasites of the JPBW in Manitoba, Saskatchewan, and northwestern Ontario. A number of parasite/parasitoid species are listed that were captured and reared between 1941 and 1966 in both Saskatchewan and Manitoba (Brandt and Melvin 1970). JPBW larvae and pupae were captured and reared, and if the captured larvae/pupae were parasitized, they would fail to reach their next instars and instead die, resulting in the parasitoid emerging. The authors explain that, while the JPBW isn't present in these areas, the populations of these parasitoids drop drastically, but after outbreaks start up again, the parasitoids are able to rebound as well. The main common insect orders were Diptera and Hymenoptera, making up a vast majority of the parasitoid species that were present, inferring that these two orders are very important in controlling the outbreaks successfully.

The shortfall in the JPBW outbreak dynamic comes down to a reliance on jack pine pollen cones (McCullough 2000). McCullough explains that the JPBW larvae generally hatch well before bud flush actually occurs, so the early-instar larvae need an alternate source of food to sustain themselves prior to bud flush. The natural solution to this issue was for the JPBW larvae to feed on the pollen cones that had remained on the trees. However, when defoliation in the previous year is high, the jack pine trees produced fewer pollen cones, creating a negative feedback cycle. The article also goes onto explain that with a decline in pollen cone quantity, high larval mortality occurs, along with decreased health in the larvae that survive, making them more susceptible to parasitoid/parasite predators. The spike in parasitoid populations and drop in pollen cone along with declines in JPBW survival rates clearly shows a density-dependant system.

Within JPBW populations there is a lagged, density-dependant relationship between the jack pine tree and the budworm (Nealis et al. 2003). In chronological order, the first relationship seen is between pollen cones and larval survival where, if few high-quality pollen cones are present, the newly hatched larvae will not survive. It should also be noted that the oldest and largest jack pine trees are defoliated more often than younger, smaller trees. Nealis et al. also mentions that pollen cone production decreases drastically the year following a defoliation event, and while the outbreaks themselves lasted 3 or 4 years, individual trees are only defoliated for 1 or 2 years during an outbreak. Essentially, the reduced number of pollen cones and the dependence on pollen cones by the newly hatched larvae results in a lagged, density-dependant relationship between the JPBW and jack pine itself. This relationship may explain why the duration of JPBW outbreaks are substantially shorter than that of the its other budworm relatives.

Predation by birds on the JPBW is also a factor in their population dynamics, although likely much less of one than parasites by analyzing the difference in number of budworms eaten during outbreaks compared to when there are much fewer budworms present (Mattson 1974). Between 1965 and 1968, a number common of birds were captured during outbreak and non-outbreak seasons and their gizzards were analyzed to determine if they change their diet to eat more of the JPBW during outbreak seasons. It was determined that there was no significant difference between the amount of the budworm consumed from low to high budworm abundance, as there was no noticeable trend in the amount of budworm found in the gizzards of the captured birds (Mattson 1974), implying that birds do not play a large role in the eventual decline of the JPBW outbreaks.

CLIMATE CHANGE AND INSECT PRESENCE

The rapidly changing climate affecting the planet to has already had severe consequences, and these effects will only continue to amplify (Dale et al. 2001). Forests are especially vulnerable to climate change, as our forest types are specifically adapted to tolerate harsher, colder climates. Dale et al. looked at fire, invasive species, insect and pathogen spread, along with hurricanes, wind, and other natural occurrences as different types of disturbances, and whether frequency, intensity, and duration of the disturbances listed above will change at all (Dale et al. 2001). An increase in even one of these types of disturbance would likely provide opportunity for another type of disturbance to arise.

With increasing climate change, trees and other species that normally reside in this area will likely suffer increased stress, and be more susceptible to other types of disturbances (Dale et al. 2001). For example, if high average temperatures stress out a stand of trees, these trees would be susceptible to disease pathogens. In turn, trees weakened by the pathogens could make them more susceptible to an insect infestation, such as the JPBW. With all these stresses, the trees would likely die, and a stand replacing fire could easily occur, altering the landscape greatly. It is expected that the frequency, intensity, and duration of many of these disturbances will increase and examples of there have already been seen with the mountain pine beetle in British Columbia and Alberta.

The potential need for assisted migration in forests everywhere has been carefully examined in recent years (Prud'Homme et al. 2018). With the currently rapid climate change, local tree species are becoming maladapted to their current home ranges. In cases where the local species may actually do better in warmer climates, trees from more southern ranges are likely to be even better adapted to those conditions, and will therefore outcompete the local species. If the local species are unable to migrate further north fast enough, they may become extirpated in that area, and eventually may even go extinct. It is imperative to properly and completely understand the trade-offs that will accrue with assisted migration, as populations with no exposure to a novel environment are often ill-adapted to deal with novel forest pests. While northern seed sources would benefit from a warmer climate, they will most likely be outcompeted by the southern species/sources.

MAPPING OF JACK PINE BUDWORM OUTBREAKS

JPBW defoliation is characterized by reddening of foliage, and this pattern across a landscape can be mapped aerially to allow forest managers to have a better understanding of the extensiveness of the outbreak (Leckie et. al. 2004). It is possible to see defoliation severity with differences in red shading (Leckie et al. 2004), and there are 4 colours that represent 4 different severities. Historically, it has been difficult to capture the severity of defoliation aerially, as trying to differentiate between shades of red is difficult from the sky. However, a study conducted by Leckie et al. (2004) consisted of testing specific types of multispectral imaging at 2.5m resolution. A narrow red band, a near infrared band, and a short-wave infrared band worked best, and were able to achieve an accuracy of 84% on the four levels of discoloration (Leckie et al. 2004). Use of mapping technology for determination of defoliation severity could make conducting similar studies to mine much easier, and therefore could be applied at a much larger scale, perhaps to entire stands.

MATERIALS AND METHODS

This study was conducted near Red Lake, Ontario, just off the Nungesser Road near Coli Lake. My study was conducted on May 18, 2019. The approximate coordinates of the study site are 51.268636N, -93.589393W. The initial study was planted with jack pine in 2006 under the supervision Dr. W. Parker. That study planted eight different seed sources of jack pine to see if there would be any variation in characteristics of the trees when all planted at the same geographic location. The layout of this study consisted of nine blocks, each of which were made up of nine plots. Each plot is a square consisting of a 5 x 5 arrangement of trees of the same seed source, with a total of 2,025 jack pine seedlings being planted at the commencement of the original study (see Figure 1). Within every block, there was a pure plot for every seed source with one block consisting of a mixed seed source block. Every plot was initially marked with an aluminum post and tag which indicated which seed source would be present in the given block. The seed sources came from three broad geographic ranges: north, central, and south. Two seed sources were located in northwestern Ontario (Red Lake and Fort Frances), identified by LUFTFR and LUNWPJ71. Three sources came from OFRI in central Ontario (in the Blind River – Thessalon area) with ID of OFRI4150, OFRI3109, and OFRI4471. Finally, three southern sources (2 east of Peterborough and 1 from northeast New York state) with ID of CFS3223, CFS3241, and CFS3239 were also used. Figure 2 is a map showing the exact origins of the seed sources, depicted as green dots.

My study consisted of looking at JPBW defoliation levels on the young jack pine in the study by Dr. W. Parker. The jack pine trees were planted 13 years ago, and are currently approximately 3-5m in height. The trees had been noticeably defoliated by JPBW in the summer of 2018, and, having assessed the trees in the spring of 2019, the foliage I was assessing was still current, as bud flush had not yet occurred.

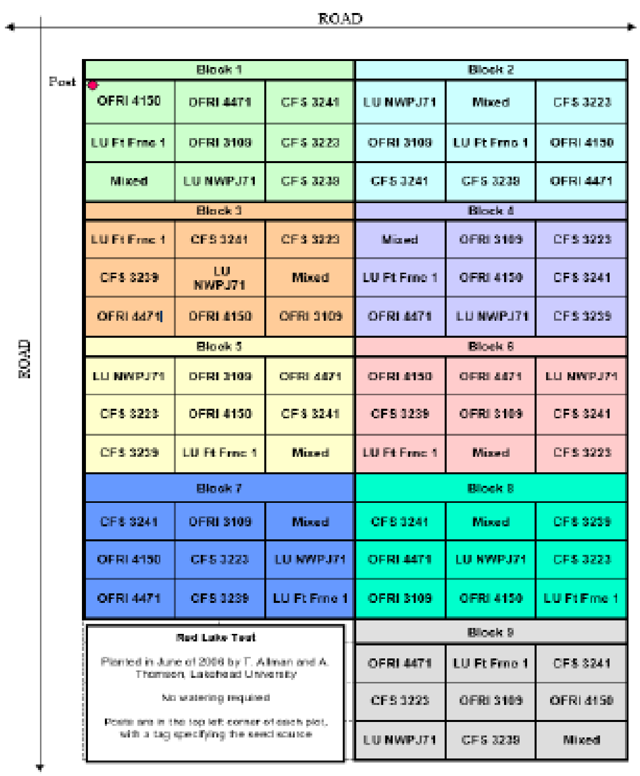

Figure 1. Study layout by block and seed source (Parker and Crowe 2007)

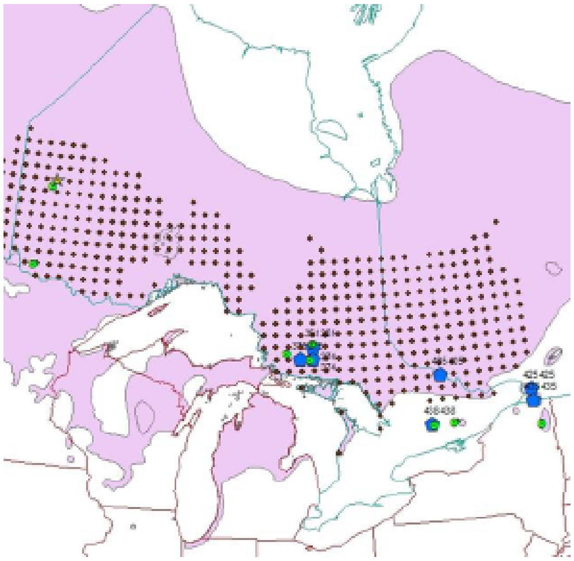

Figure 2. Location of seed sources (Parker and Crowe 2007). Note that the green icons are the seed sources used in this study.

After consulting with my thesis supervisor and a JPBW expert from Manitoba, I determined that the best method of measuring defoliation was a visual assessment. For this visual assessment, I walked through each plot in order to properly see each tree from top to bottom. For measuring defoliation, I used a modified Fettes Method, which is normally used in measuring spruce budworm defoliation on balsam fir (Maine Forest Service 2013) to determine defoliation severity. I used only 4 categories of defoliation to simplify my findings, whereas the typical Fettes Method uses 10 categories based on the proportion of needles that have been defoliated (Maine Forest Service 2013). My defoliation categories were: no to minimal defoliation (0-5% defoliation), low defoliation (5-25%), moderate defoliation (25-50%), and severe defoliation (50-100%). I assessed every plot in every block, however the mixed blocks were not used in the statistical analysis of my findings, as it was impossible to know how many trees from each seed source were in the mixed blocks. Due to mortality, there were much fewer trees assessed than what were planted.

RESULTS AND DISCUSSION

In total, 822 trees were assessed for defoliation severity. The total number of trees in each defoliation category and for each seed source can be seen in Table 1. This table shows the simplest way to display the findings of this study.

Table 1. Summary of trees damaged by JPBW by seed source

Source	Defoliation Severity				
	NO	LOW	MOD	SEV	Total Trees
LUNWPJ71	38	66	35	5	144
LUFTFR	32	67	28	3	130
OFRI4150	19	60	39	3	121
OFRI3109	17	55	50	9	131
OFRI4471	13	60	43	11	127
CFS3223	1	8	17	8	34
CFS3241	2	3	5	4	14
CFS3239	0	6	7	15	28
MIXED	14	41	28	10	93
Total	136	366	252	68	822
Average	15.11	40.67	28.00	7.56	91.33
Standard Deviation	13.38	27.33	15.69	4.13	51.57

To adjust for unequal numbers of surviving trees across the seed sources as well as unequal number of sources, the results of Table 1 were displayed in Table 2 with the percentage of trees in each defoliation category being used instead of the actual number. Table 3 shows the proportion of trees in each category, but the seed sources are condensed into general geographic locations to better interpret the effects of seed source location. Figure 3 shows the total number of trees in each defoliation category with the geographic locations

Table 2. Percentage of trees in each defoliation category by seed source

	Defoliation Category (%)					
Source	%NO	%LOW	%MOD	%SEV	%NO+LOW	%MED+SEV
LUNWPJ71	26.4%	45.8%	24.3%	3.5%	72.2%	27.8%
LUFTFR	24.6%	51.5%	21.5%	2.3%	76.2%	23.8%
OFRI4150	15.7%	49.6%	32.2%	2.5%	65.3%	34.7%
OFRI3109	13.0%	42.0%	38.2%	6.9%	55.0%	45.0%
OFRI4471	10.2%	47.2%	33.9%	8.7%	57.5%	42.5%
CFS3223	2.9%	23.5%	50.0%	23.5%	26.5%	73.5%
CFS3241	14.3%	21.4%	35.7%	28.6%	35.7%	64.3%
CFS3239	0.0%	21.4%	25.0%	53.6%	21.4%	78.6%

Table 3. Proportion of trees in each defoliation category by location

Source	Defoliation Severity			
	NO	LOW	MOD	SEV
NWO	0.26	0.49	0.23	0.03
Central	0.13	0.46	0.35	0.06
South	0.04	0.22	0.38	0.36

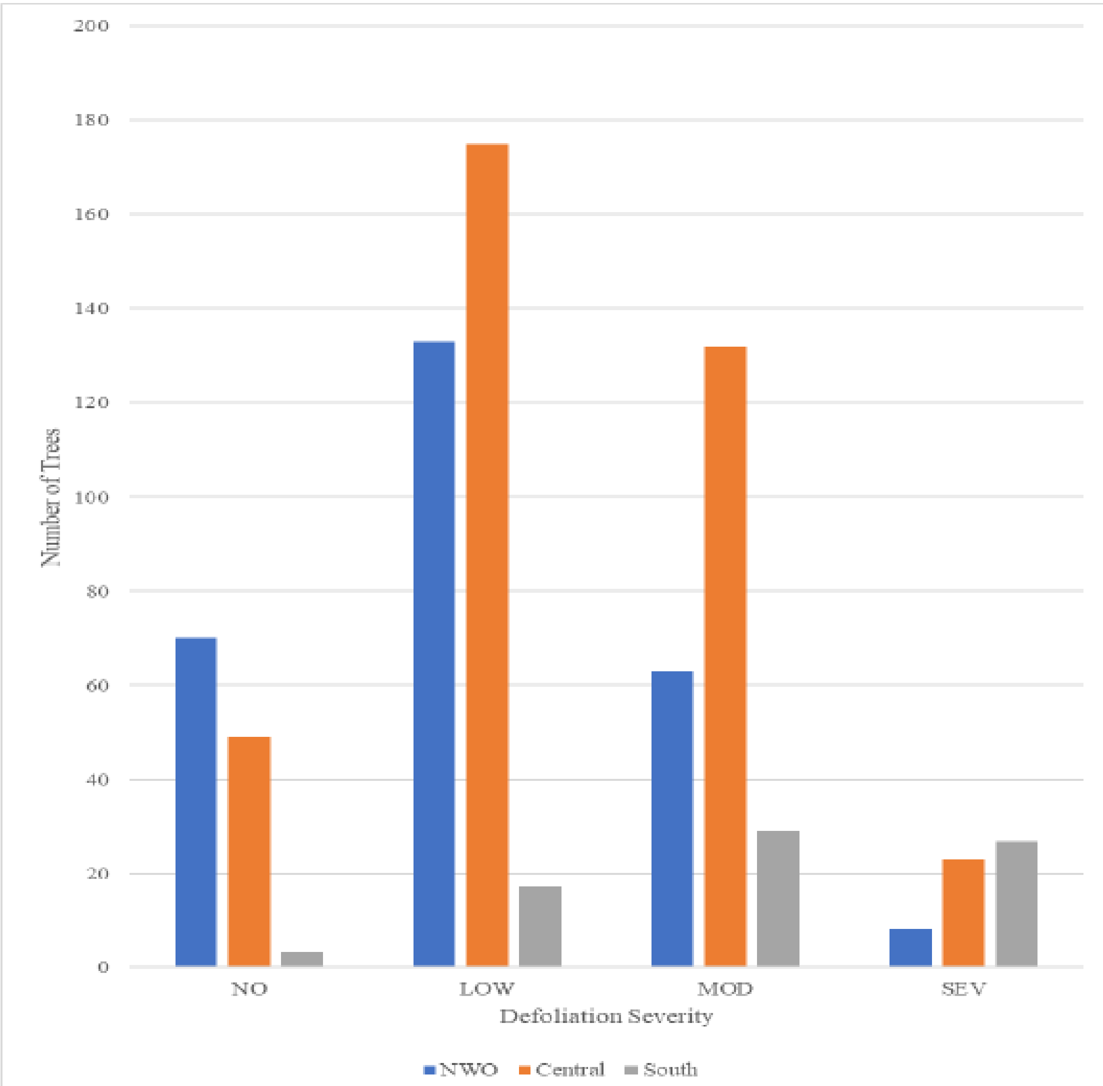

Figure 3. Number of trees falling in each defoliation category for each general geographic source

Another way the above data was analyzed was by assigning a numerical value to every tree based on the defoliation category it fell in to. Under this method, a tree with no defoliation receives a 1, a tree with low defoliation gets a 2, moderate gets a 3, and severe defoliation receives a 4. Table 3 shows the by block results when using this defoliation rating method.

Table 4. Average defoliation rating by seed source and block

Block	Rating		
	NWO	Central	South
1	2.30	2.26	3.00
2	2.06	2.36	3.13
3	2.23	2.40	3.33
4	2.03	2.29	3.00
5	1.92	2.41	3.40
6	2.00	2.29	2.82
7	2.00	2.34	2.86
8	1.81	2.41	2.83
9	1.95	2.31	3.33
Average	2.03	2.34	3.08

Using the above table, a one-way ANOVA was conducted using the Microsoft Excel add-on XLSTAT to determine if there were significant differences between the three geographic seed source locations and JPBW defoliation severity. Tukey's HSD post-hoc test was conducted after the ANOVA to determine which of the three sources were all significantly different from the others, using a p-value of 0.05 to determine statistical significance. The summary statistics for the ANOVA can be seen in Table 5. The ANOVA results are shown in Table 6, which indicate that there are significant differences in the data I collected. The results of the Tukey's HSD post-hoc test can be found in Tables 7 and 8, which show the values that were needed to accept that there is a difference between the three locations, as well as the actual values that were computed in the test.

Table 5. XLSTAT ANOVA summary statistics

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Y	27	0	27	1.806	3.400	2.484	0.473

Table 6. ANOVA Results

Source	DF	Sum of	Mean	F	Pr > F
Provenance	2	5.190	2.595	97.849	**<0.0001**
Error	24	0.636	0.027		
Corrected Total	26	5.826			

Table 7. Tukey's HSD Test Results

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
South vs NWO	1.045	13.617	2.497	**<0.0001**	Yes
South vs Central	0.736	9.586	2.497	**<0.0001**	Yes
Central vs NWO	0.309	4.030	2.497	**0.001**	Yes

Table 8. Tukey's HSD Test summary results

Category	LS means	Standard error	Lower bound (95%)	Upper bound (95%)	Groups		
South	3.078	0.054	2.966	3.190	A		
Central	2.342	0.054	2.230	2.454		B	
North	2.033	0.054	1.921	2.145			C

At the time of my data collection, the study area was near the start of the second or third year of a JPBW outbreak, one that would be expected to last about 2-6 years total (Nealis 2016). Upon inspection of the study area, only the previous growing season's foliage had been defoliated, as the current year's growth had not flushed yet. Given that the JPBW had not yet started to eat pollen cones or older foliage, the outbreak was clearly in its early stages (Brandt and Melvin 1970). The outbreak being in the early stages was also confirmed by local experts who had been working in the area, as well as MNRF notices/websites. Knowing this in advance of my data collection made the collection process simpler, as only the terminal portions of the branches were damaged, allowing for ease of visual assessment.

While Table 1 shows a summary of the direct results of my data collection, this table doesn't really say much about the differences between the seed source locations. Due to the very small sample size of the southern seed sources, it was initially very difficult to tell if there were any significant differences in resistance to defoliation across the seed sources. I determined that combining no and low defoliation results and comparing them to moderate and severe defoliation was a simple, yet effective, method of comparing defoliation intensity between seed sources and geographic location. Thus, even while using the combination of defoliation categories, looking at the proportion or percentage of trees in each defoliation category is a much clearer way to analyze the data. For example, the northern seed sources had an average of 35.5 trees that were in the moderate to severe defoliation category, while the southern seed sources averaged 18.7. At first glance, it would appear the northern seed sources suffered worse defoliation, but when looking at Table 2 and Table 3, it can be seen that the proportion of moderate and severe for the northern sources is 0.26, or 26%, while the same category for the southern sources are 0.74, or 74%, which clearly shows that the southern sources that were measured suffered much worse defoliation on a per tree basis.

Using the latitude values for each of the seed sources, I was able to create a scatter plot that showed the severity of defoliation compared with latitude (Figure 4). Using the combination of proportion of moderate to severe defoliation per seed source, I was able to plot a regression in order to determine what amount of variation in the data could be explained by differences in the latitudes of the seed sources. The chart showed results similar to what was expected. The trendline used was a polynomial curve, and the R^2 value and equation can be found in Figure 4 along with the scatter plot. It can be seen from the chart that with the samples given, defoliation intensity has a strong relationship ($R^2 = 0.8183$) with latitude. However, further testing would need to be conducted with more seed sources and at varying locations to get a more accurate representation of how much of an effect latitude has on resistance to JPBW.

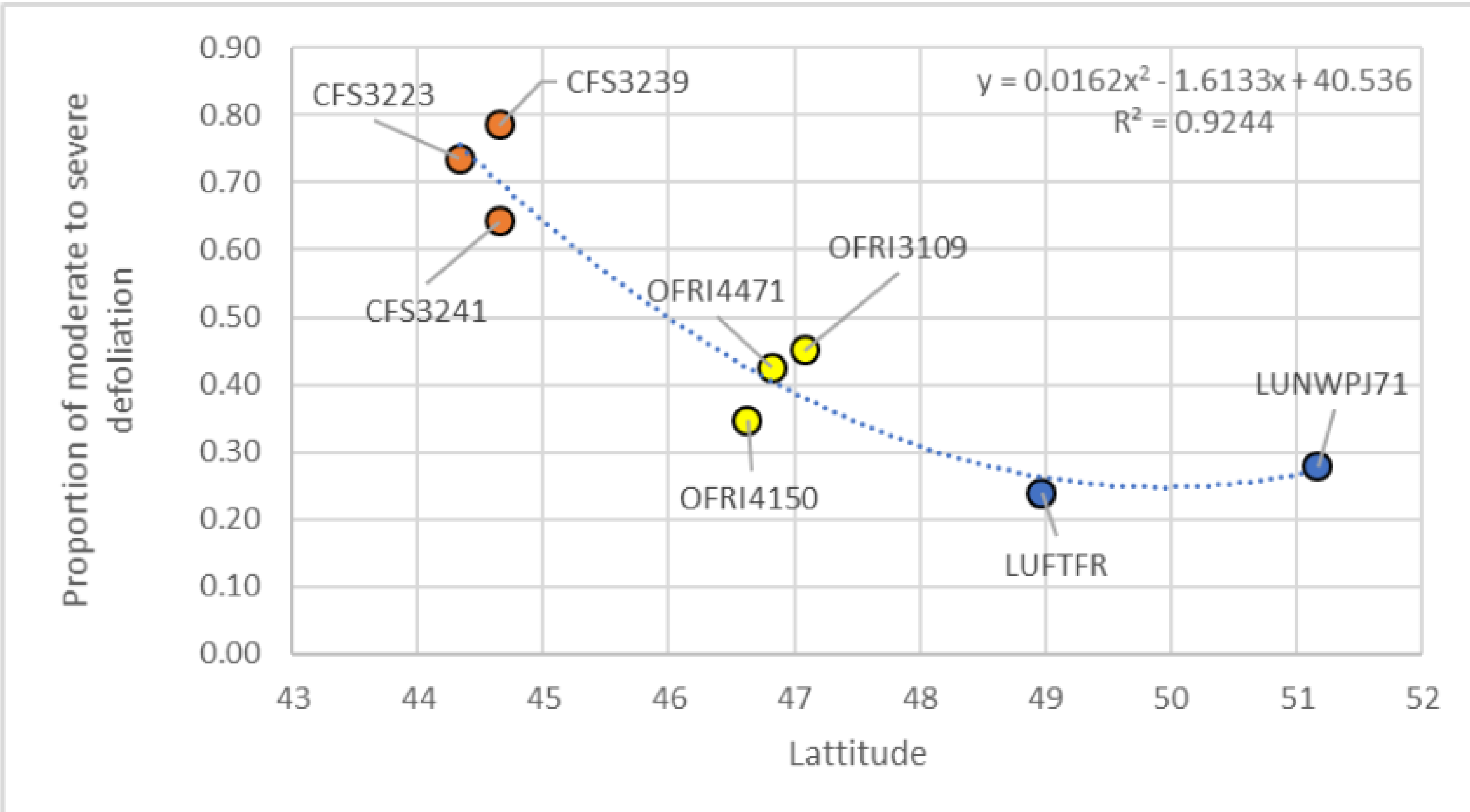

Figure 4. Scatter plot showing how JPBW defoliation intensity changes with latitude

The method I found to be best at analyzing the seed sources as a whole however was the damage rating method discussed earlier. Instead of having to look at the defoliation intensity as percentages or proportions, assigning values to each tree within each source and finding the average allows me to have one single value for every source, making comparing much easier. Table 4 shows the damage ratings for the sources by block with an average score per seed source. Figure 4 (below) graphically displays the differences in the seed sources based on damage rating. The bar graph shows that while throughout the blocks the damage ratings fluctuated a small amount, within blocks, the northern sources always had a lower damage rating than the central sources, and the central sources were always lower than the southern sources. The southern sources always had a much higher damage rating than the other two sources, and the north and central sources were much closer together.

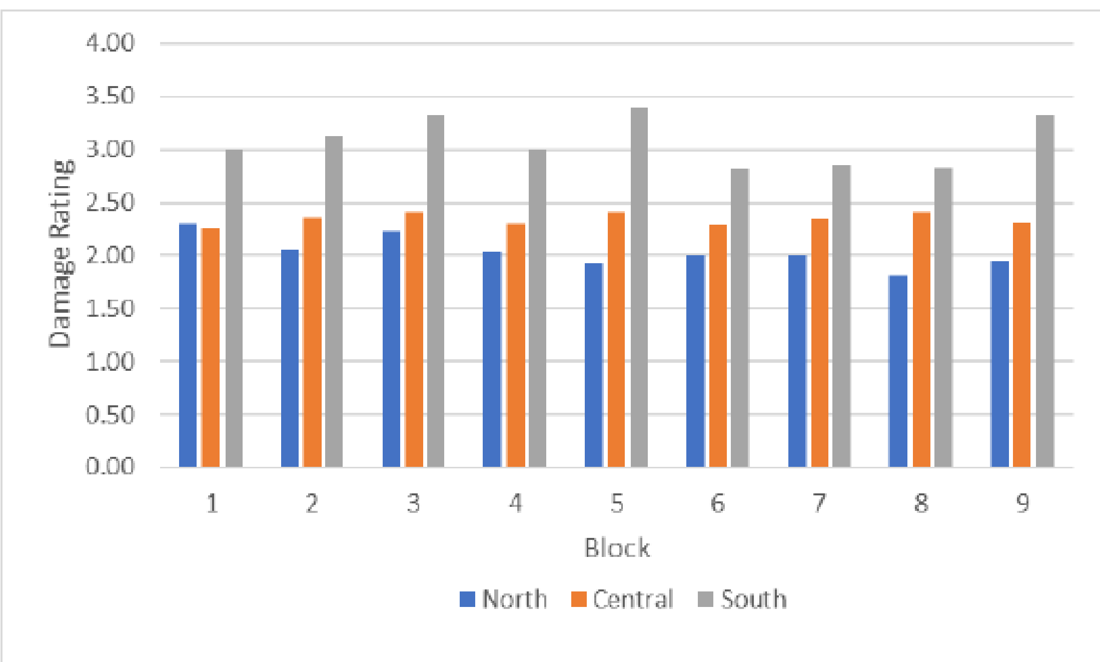

Figure 5. Bar graph showing damage rating of seed sources through individual blocks

While using the graphs here to visualize the data is useful, the ANOVA results are what can truly explain statistical significance. Table 5 consists of some simple summary statistics that are really only useable for curiosity, but do not indicate statistical significance. However, Tables 6, 7, and 8 show the results of the ANOVA, which do provide statistical significance to the results.

First of all,, Table 6 displays the results of the ANOVA. For a source to be significantly different, the p-value needed to be less than 0.05. The p-values obtained were all less than 0.0001. I can therefore conclude that there are significant differences in defoliation intensity between at least two of the three geographic seed source locations. As the ANOVA yielded a significant p-value, I also ran a posthoc Tukey's HSD test (Tables 7 and 8) on the same data to determine which sources, if not all, were significantly different from each other. The sources are each given a letter to represent their individual values, and if two sources are significantly different, they will have different letters. The Tukey's HSD Test showed that each source was significantly different from the others. When looking at Table 7 one can see that while all the pairwise comparisons are significantly different, central and north seed sources were most similar, as this comparison had a p-value of 0.001. For comparison, north vs south and central vs south had p-values of less than 0.0001. These results of Tukey's HSD Test put the sources into three groups; A, B, and C, showing that every seed source is significantly different from each other. This means that there is a relationship between seed source/geographic origin of the seeds and defoliation resistance to JPBW.

A concern pertaining to the results that arose after the data collection was the effect that non-tested factors may have had on the results of the study, specifically how stress impacts a tree's ability to resist JPBW defoliation. According to Dale et al. (2001), there tends to be a relationship between forest disturbances involving multiple factors. In some cases, some sort of pathogen will go through a forest, which is then followed by another type of disturbance. In my study, there was no true disturbance that happened to many of the trees in the study, but rather they were planted in an area that they are not native to, resulting in high stress levels for some of the seed sources. With this stress acting as a form of disturbance, the JPBW was able to come into the study area and easily attack the stressed trees. This shows that even within the jack pine species, southern sources are more severely impacted by the JPBW.

While in this particular study, there were clear and obvious significant differences between all three jack pine seed sources, there still may be other factors at play affecting the apparent trend in defoliation severity. Parker and Crowe (2008) attributed the poor growth of southern seed sources to the southern sources not being adapted to the less hospitable conditions further north. To determine whether or not poor site matching is the indirect cause of defoliation, my recommendation for future studies like this would be to test the same seed sources at different geographic locations. That way, the southern source wouldn't be as far removed, and may be allowed to have a better opportunity to defend itself against defoliation. However, as mentioned above, JPBW has very little presence in the southern range of jack pine, so some sort a cage test would need to be conducted. If after the cage test there was still significant proof that the northern sources resist defoliation better than the other sources, we can be fairly certain that the resistance is almost purely genetic, and evolved from many generations of jack pine having to deal with JPBW outbreaks.

One aspect of this study that will need to be improved upon in order to perform similar work in the future is to create a standardized JPBW defoliation assessment method. I came into this study without any experience in sampling insect damage to trees, and while the visual assessment is relatively straightforward, there are certainly many opportunities for error with relying on visual assessments. Consistency is absolutely essential in comparing studies done by multiple people or in various locations.

CONCLUSION

Based on the data collected in the Red Lake area and by the statistical analyses conducted since at Lakehead University, I rejected my null hypothesis, that there is no difference in JPBW defoliation severity across the various seed sources. In rejecting my null hypothesis, I accepted the alternate hypothesis, that there was a statistically significant difference in the resistance to JPBW defoliation amongst jack pine seed from northwestern Ontario, central Ontario, and southern Ontario. Not only is there a single difference, but each geographic seed source is statistically significantly different from each other as well.

The implications of these findings may prove to be biologically significant as well. With our climate changing at a rapid pace, the need for assisted migration of many tree species may be necessary to keep up with this change. However, knowing that jack pine seed originating from central or southern Ontario may not be suitable for planting in the north due to either susceptibility to JPBW damage or maladaptation-induced stress causing increased susceptibility is crucial for forest managers. A forester could think they are doing the forest a favour by planting a seed source that is better adapted to a warmer climate, but if the jack pine population of this seed source has never had any exposure to the JPBW, the entire population could be decimated, causing significant ecological and economic damage. Further research needs to be conducted on this topic, but I believe this is a good start, and should certainly be considered when discussing the use of assisted migration techniques in forestry.

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LITERATURE CITED

Brandt, N., J. Melvin. 1970. Parasites of the jack-pine budworm, *Choristoneura pinus pinus* Free., in Manitoba, Saskatchewan and Northwestern Ontario. Canadian Forestry Research, Forest Research Laboratory. Pp. 1-9.

Dale, V., L. Joyce, S. Mcnulty, R. Neilson, M. Ayres, M. Flannigan, P. Hanson, L. Irland, A. Lugo, C. Peterson, D. Simberloff, F. Swanson, B. Stocks, B. Wotton. 2001. Climate Change and Forest Disturbances: Climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. BioScience 51: 723-734.

Freeman, T. 1953. The spruce budworm, *Choristoneura fumiferana* (Clem.) and an allied new species on pine (Lepidoptera : Tortricidae). The Canadian Entomologist 85(4) p.121-127.

Leckie, D., E. Cloney, S. Joyce. 2004. Automated detection and mapping of crown discolouration caused by jack pine budworm with 2.5 m resolution multispectral imagery. International Journal of Applied Earth Observation and Geoinformation. 7: 61-77.

Mattson, W. 1974. Negligible feeding responses by birds to variations in abundance of the budworm, *Choristoneura Pinus* (Lepidoptera: Tortricidae). The Great Lakes Entomologist 7(4): 109-111.

McCullough, D. 2000. A review of factors affecting the population dynamics of jack pine budworm (Choristoneura pinus pinus Freeman). Population Ecology 42(3): 243.

McCullough, D., H. Kulman. 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). Oecologia 87: 135-145.

MSU Forestry Extension Team. 2014. Forest types of Michigan. Michigan State University Extension. Pp 1-3.

Nealis, V. 2012. Parasitism in sustained and collapsing populations of the jack pine budworm, *Choristoneura pinus pinus* Free. (Lepidoptera: Tortricidae), in Ontario, 1985–1987. The Canadian Entomologist 123: 1065-1075.

Nealis, V. 2015. Comparative ecology of conifer-feeding spruce budworms (Lepidoptera: Tortricidae). The Canadian Entomologist 148(1): 33-57.

Nealis, V., S. Magnussen, A. Hopkin. 2003. A lagged, density-dependent relationship between jack pine budworm *Choristoneura pinus pinus* and its host tree *Pinus banksiana*. Ecological Entomology 28: 183-192.

Parker, W., K. Crowe. 2008. Using portfolio theory to guide reforestation and restoration under climate change scenarios. Climate Change 89: 355-371.

Prud'Homme, G., M. Lamhamedi, L. Benomar, A. Rainville, J. Deblois, J. Bousquet, J. Beaulieu. 2018. Ecophysiology and growth of white spruce seedlings from various seed sources along a climatic gradient support the need for assisted migration. Frontiers in Plant Science 8. Online.