THE EFFECT OF BLOCK COMPOSITION ON THE SEVERITY OF SPRUCE BEETLE (*DENDROCTONUS RUFIPENNIS*) DAMAGE IN NORTHERN INTERIOR BRITISH COLUMBIA

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THUNDER BAY, ONTARIO

April, 2021

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An Undergraduate Thesis Submitted in Partial

Fulfillment of the Requirements for the Degree of

Honours Bachelor of Science in Forestry

Faculty of Natural Resources Management

Lakehead University

April, 2021

Major Advisor Second Reader

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ABSTRACT

Lee-Mitchell, C. A. 2021. The effect of block composition on the severity of spruce beetle (*Dendroctonus rufipennis*) damage in northern British Columbia. 42 pp.

Keywords: Spruce beetle, *Dendroctonus rufipennis,* Prince George, spruce, Hybrid spruce, Mischinsinlinka, Omineca, Gaffney, stand management, climate change

The spruce beetle (*Dendroctonus rufipennis*) is a natural part of the western North American landscape, feeding on the phloem of trees in the *Picea* genus. The spruce beetle generally feeds on downed trees but can also feed on standing living trees if beetle populations and host trees are plentiful. If this occurs, it can result in an outbreak of spruce beetle populations. With the help of blue-stain fungi, these outbreaks can cause high mortality in spruce tree populations and devastate forests. Multiple factors can contribute to an outbreak of spruce beetle, with most linked to climate change. The government of British Columbia has a list of management practices to mitigate the effects of the spruce beetle, but prevention remains elusive. It is known that a more diverse tree stand can mitigate severity of insect attacks, most notably for spruce beetle if there are more diverse coniferous species. Here, an assessment of five blocks of forest set for harvest in two different areas with different levels of tree species diversity in the Omineca landscape unit of BC agrees with these results. The two areas in the Omineca landscape unit consisted of the Mischinsinlinka (MIS) area with low tree diversity and the Gaffney (GAF) area with high tree diversity. The MIS area, which had only two prominent tree species on the sites, experienced high amounts of beetle predation. The GAF, with up to four prominent species of trees, had lower amounts of beetle predation. It was also discovered that the correlation between tree diameter at breast height (DBH) and tree height to beetle attack severity is much stronger in the MIS than the GAF. This suggests that damage correlation is strongest in less diverse stands and less so in more diverse stands.

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ACKNOWLEDGEMENTS

This would not be possible without the assistance from Industrial Forestry Service who supplied the field data. A special thank you must also go to Dr. Don Henne for being the thesis supervisor, as well as to Dr. Mathew Leitch and Dr. Lenni Meyer for being the thesis class professors. I would also like to acknowledge the time and advice given by Tyler Ripku with the data analysis.

1. INTRODUCTION

The spruce beetle (Coleoptera: Scolytidae) (*Dendroctonus rufipennis*) is a bark beetle native to western North America. The larvae feed on the phloem of spruce trees, with the likelihood of tree death increasing with the presence of blue stain fungi that are carried by the adult beetles (Werner *et al.* 1994; FNRRD 2018). The beetle affects a variety of spruce species, including Engelmann (*Picea englmannii* Parry ex Engelm), white (*Picea glauca* (Moench) Voss), sitka (*Picea sitchensis (*Bong.) Carrier), and Colorado blue (*Picea pungens* Engelm.) (Tomlinson 2013; BC 2020). The year 2017 saw over 500,000 hectares of forests affected by spruce beetle outbreak in British Columbia, with 340,000 ha of this in the Omineca Region alone (FNRRD 2018). The beetle's capacity to cause large amounts of damage makes it a real threat to the forestry sector by killing off high-value spruce before it can be harvested.

In the summers of 2018 and 2020, blocks that were allocated for harvest due to spruce beetle damage were assessed by Industrial Forestry Services in the Gaffney and Mischinsinlinka landscape units, as seen in figure 1. Both landscape units are located north of Prince George, British Columbia, and have a mixture of subalpine fir (*Abies lasiocarpa*), balsam fir (*Abies balsamea*), poplar species (*Populus* sp.), spruce species (*Picea* sp.), and lodgepole pine (*Pinus contorta*) present in the area. These landscape units are also located close to the Omineca landscape unit, the aforementioned area that had the majority of

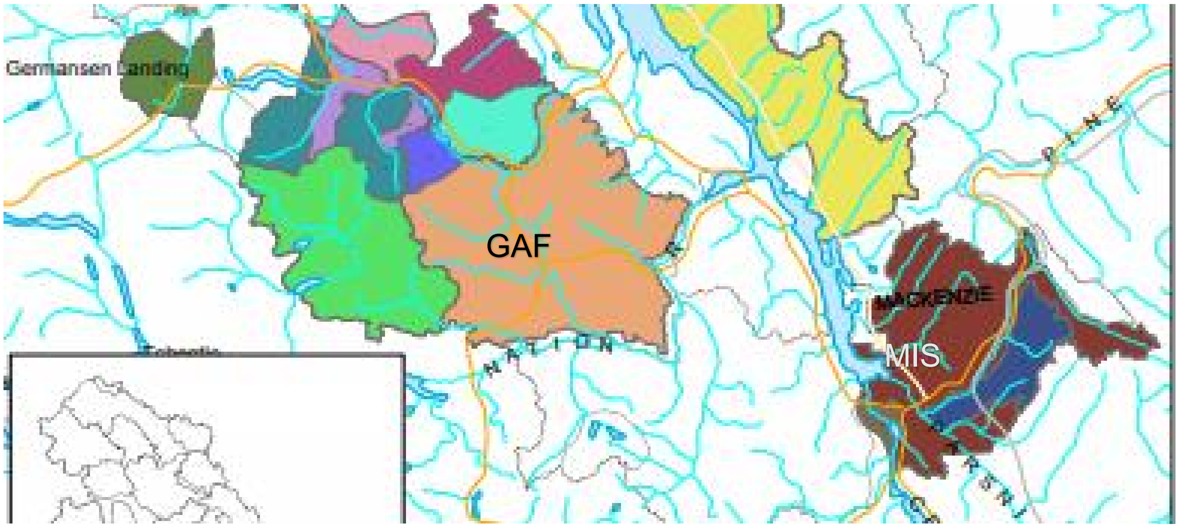

Figure 1. The Gaffney (GAF) and MI-ischinsinlinka (MIS) forest units.

spruce beetle damage (MAL 2008). The assessments were done using a variety of basal area factors (BAF's) and spacing techniques following the guidelines set out in the British Columbia Timber Cruising Manual (BC 2017). Information collected during assessments included tree age, tree height and diameter at breast height (DBH), stand tree species composition, types of damage, and insect presence/damage. During the assessments completed in 2020, it was observed that areas with higher concentrations of spruce trees had a higher amount of spruce beetle presence per tree, while areas with a lower concentration of spruce exhibited less damage per tree. This suggests that stand tree species composition can influence spruce beetle damage severity. If this is true, then planting a more diverse block in harvested areas can result in less spruce beetle damage in the future. Since a limiting factor for the size of a spruce beetle infestation is the availability of host resources, diverse tree blocks could theoretically decrease the need for intensive treatments like pesticides, tree traps, and rushed harvests (FNRRD 2018).

2. OBJECTIVE AND HYPOTHESIS

The objective of this thesis is to statistically analyze the data collected from these areas and determine if the following observations are correlated: block composition, severity of spruce beetle damage, and percent of spruce trees affected. If the statistical analysis demonstrates that areas with lower spruce concentration have less severe beetle damage, then a correlation exists between spruce beetle damage severity and block species composition. If the analysis demonstrates that areas with lower spruce concentration show the same severity of beetle damage as areas with higher concentrations of spruce, then block species composition is not correlated with spruce beetle damage severity.

3. LITERATURE REVIEW

Insects are responsible for massive amounts of land-based disturbances which affects roughly 10% of the world's land area every year, making insect damage comparable to fires and droughts (Walker 2012). Much like fire and droughts, insect damage can bring fundamental change in an area and this ability for mass effect is what makes bark beetles so significant in ecosystems. Areas dominated by a single tree species are viewed as unhealthy because it: lowers the biodiversity of the landscape, lowers the potential to support a variety of species, and limits the area’s resilience and ability to manage disturbances (Jactel and Brockerhoff 2007; Walker 2012). When this occurs, some sort of disturbance is needed to create more diversity on the site. Insects are a perfect example of nature implementing one of these disturbances, often by targeting a single host species or group of species (Walker 2012; Six and Bracewell 2015). These insect-driven disturbances, especially by bark beetles, form when the target species reaches a large enough population size that it can support an insect population boom (USDA 2011; Walker 2012). This allows forest succession to take place, and introduces new tree species into the process (Walker 2012).

3.1. THE SPRUCE BEETLE

3.1.1. General description

The spruce beetle (*Dendroctonus rufipennis*) (Coleoptera: Scolytidae) has three distinct genetic groups that are spread across North America, with each group feeding on different species of spruce (Six and Bracewell 2015). The genetic groups located in the area of study reported in this thesis prefer white and Engelman spruce but are known to feed on a variety of other spruce species if these are unavailable (NRCAN 2015; Six and Bracewell 2015). The beetle prefers fallen trees, stumps or sick and dying trees which are commonly found after large disturbances such as windstorms and forestry operations (NRCAN 2015; Six and Bracewell 2015; FNNRD 2017). Spruce beetle can also attack fully grown healthy trees if conditions are favorable, preferring large diameter trees with small amounts of radial growth (Burleigh *et al.* 2014; Six and Bracewell 2015).

3.1.2. Appearance

Adult beetles are roughly 6 mm long with a black, segmented body and red to brown wing covers (Six and Bracewell 2015; FNRRD 2018). An example of an adult beetle can be seen in figure 2. The colour of immature beetles range from brown to pale yellow and the larvae, which are tube-like, legless and white or tan in colour, are between 6 to 7 mm long . They live beneath the bark, burrowing in chambers as seen in figure 3 (FNNRD 2018).

Figure 2. Adult spruce beetle (FNRRD 2018).

Figure 3. Spruce beetle larvae (FNRRD 2018).

3.1.3. Life Cycle

Spruce beetles have a reproductive cycle that can require between two and three years to complete, with one year cycles being uncommon (Six and Bracewell 2015; FNRRD 2018). A typical two year life-cycle begins with the adults feeding on phloem from late May to early July, creating galleries under the bark of a tree. Adults will then emerge in the fall and move to the base of the tree to over-winter (Burleigh *et al.* 2014).

Females lay eggs in galleries created beneath the bark, packing the eggs in with frass and boring dust (Holsten *et al.* 1989; FNRRD 2018). These galleries are wider than the adult beetle and are between 3.0 and 6.35 cm long, holding between four and fourteen eggs in short rows on alternating sides of the gallery (Holsten *et al.* 1989; NRCAN 2015).

Hatched larvae stay in a group for the first and second instar stages, feeding in one gallery together. Each larva will then make individual galleries in the third and fourth instars, creating a home where the developing beetle will predominantly overwinter (Holsten *et al.* 1989). The larvae reach pupal stage one year after the initial attack by the parents. It takes ten to fifteen days for the pupal stage to complete (Holsten *et al.* 1989; FNRRD 2018).

The beetle may overwinter for a second time in the pupal sites if the tree is down but may also move to the base of the tree if it is standing. The beetles then emerge in the spring to feed on new host material, in which the new two year cycle begins (Holsten *et al.* 1989).

A one-year life cycle for the spruce beetle is more common on south-facing landscapes or the upper side of downed logs due to increased sunlight exposure and associated summer temperatures and comprises the same stages as a typical two-year life cycle (Holsten *et al.* 1989; NRCAN 2015). Adults emerge and attack the host tree from June to August and then the larvae overwinter the same year (Holsten *et al.* 1989). In the following spring, the larvae start to develop into the pupal stage in May and then emerge as adults in June (Holsten *et al.* 1989; Jenkins *et al*. 2014).

3.2. BLUE STAIN FUNGI

One element of spruce beetle attack related to increased damaging to spruce trees concerns the tendancy of adult beetles to carry spores of blue stain fungi, a set of species of fungi that belongs to the genera *Ophiostoma* and *Ceratocystis* (Werner *et al.* 1994; USDA 2013; FNRRD 2018). The fungi, once inside the tree, begin to colonize and produce mycelium, the vegetative part of the fungus. The mycelium develops into thread-like masses of hyphae in the phloem and sapwood, preventing the flow of water throughout the tree (USDA 2013). The reduction of water flow and additional stress of fighting off a beetle infestation may lead to death of the host tree (USDA 2013; FNRRD 2018).

3.3. MANAGEMENT

To manage the spruce beetle, the Government of British Colombia has recommended the following series of actions: harvesting, trap trees, and prevention. Each method helps prevent or mitigate the effects of the beetle and are described bellow (FNRRD 2017).

3.3.1. Harvesting

Harvesting is either done as a sanitization harvest or a salvage harvest, the former being done in stands with active beetle populations and the latter being done in stands with no active beetle populations. Sanitization harvests are done in active sites to immediately lower spruce beetle populations, while salvage harvests are done after a spruce beetle outbreak has passed through an area and is done to utilize tree fibre before it becomes unusable (FNRRD 2017).

3.3.2. Trap Trees

A trap tree is a tree that is felled to prevent a beetle attack, attracting local beetle populations to one location thereby preventing the movement of the beetle population to other tree populations (FNRRD 2017). The purpose of trap trees is to control small populations of beetles and should be executed in the spring before adults take flight (Jenkins *et al.* 2014). This practice protects adjacent healthy forests by containing beetle populations before sanitization harvesting and allows for the collection of any remaining beetle populations after a harvest (FNRRD 2017). The selected trap trees are spruce trees with thick bark, over 35 cm DBH, and residing in shaded areas. The number of trees to be felled increases with the level of beetle infestation. (Jenkins *et al*. 2014; FNRRD 2017). Once felled and attacked, the trap trees are treated before the following spring (Jenkins *et al.* 2014). Treatment can be in the form of burning, de-barking, or removal from the site (Jenkins *et al.* 2014; FNRRD 2017).

3.3.3. Prevention

3.3.3.1. Hauling and Milling

Prevention of spruce beetle infestation can include the limiting of transfer and processing of wood in and around infested areas. Wood being hauled to or from an infested area should only be moved during the time of the year when beetles are dormant and not flying, but in the case when the wood must be hauled during the time when adult beetles have emerged, the wood should be processed at a mill within 24 hours (FNRRD 2017).

3.3.3.2 Prevention: On-site prevention

To limit spruce beetle population growth, multiple practices can take place at harvesting sites where current or previous beetle activity has occured. Stumps should be cut as low as possible or should be trimmed and burned in a pile. Tree tops or trees that are 10 cm DBH or greater must be either scattered or burned. Any tree that falls along the edge of a block should be collected (FNRRD 2017). This limits potential habitat for spruce beetles, eliminates food sources, overwintering sites, and creates conditions undesirable to prospective colonies (Jenkins *et al.* 2014).

3.4. THE HOST TREES OF SPRUCE BEETLE

Spruce beetles attack a variety of spruce trees in North America, but in the area under study for this thesis, the tree species targeted by the spruce beetle are Engelmann spruce and white spruce. Engelmann spruce is found throughout the Rocky Mountain range between 100 m and 2000 m in elevation, growing best in steep terrain or near streams (Tomlinson 2013; BC 2020). White spruce can be found throughout the boreal and sub-boreal forests, growing in a wide variety of climatic and soil conditions (Tomlinson 2013; BC 2020). The Engelmann and white spruce hybrids are known as hybrid white spruce (*Picea glauca x engelmannii*) and can display a mixture of traits from both species, making identification extremely hard in the field (Argus *et al.* 1992; Tomlinson 2013). For this reason, all spruce trees analyzed in this study are considered hybrids of the two species and no distinction will be made between the two. The species of spruce is not of particular importantance since there is no evidence to support that the beetle in the area under study ha a prefferance for either white spruce or Engelmann spruce (Six and Bracewell 2015).

3.5. SPRUCE BEETLE INFESTATIONS AND OUTBREAKS

3.5.1. Signs of Infestation

Signs of spruce beetle activity can come in the form of direct and indirect indicators, with obvious signs becoming apparent after twelve to fifteen months of infestation (NRCAN 2015; FNNRD 2018). Some indications of activity that appear later in the infestation include boring dust, flaking bark, and discoloured tree tops (NRCAN 2015). Boring dust will look like fine sawdust and is produced by the beetle as it eats through the tree bark (BC 2020). Flaking bark is a side effect of insectivorous birds digging through the bark to look for beetle larvae and other insects (NRCAN 2015). Treetops start to look discoloured after one year, turning a yellowish tinge and eventually red once the tops have completely died (NRCAN 2015; BC 2020). There are two alternative ways to identify if spruce beetle is present in a stand if none of the above signs have occured. One is by physically cut bark away from the base of the tree to expose galleries or look for pitch tubes (NRCAN 2015; BC 2020). Pitch tubes are a build-up of sap and frass that forms on the enternace holes created by the spruce beetle, an example can be seen in figure 3 (NRCAN 2015).

Figure 4. Pitch tubes forming at the base of a spruce tree (NRCAN 2015).

It takes thirteen to fifteen months for signs of a beetle infestation to appear, thus enabling a whole generational cycle of beetles to become prevalent in an area previously undetected (FNNRD 2018).

3.5.2. Reasons for a Spruce Beetle Outbreak

Spruce beetle populations naturally occur as an eruptive population pattern, going through periods of outbreak followed by lulls. When a beetle population goes through an outbreak stage, it's due in combination to: lack of predators, favourable climatic conditions, and a ready supply of resources (FNNRD 2018). Outbreaks have become more common and there is speculation as to the cause of increased spruce beetle infestation rates over the past few decades, with drought, warmer temperatures, and more frequent storm events being cited. These factors have become more prevalant over the past few decades and are associated with climate change (Dai 2011; Tempireli *et al.* 2015; Hart *et al.* 2017; FNNRD 2018).

Drought has been thought to be a driver of spruce beetle outbreaks because it reduces resource availability for the tree and weekens its ability to combat spruce beetle infestations (Tempireli *et al.* 2015, Hart *et al.* 2017). Instances of drought creates conditions that limit the amount of water available to affected trees which impedes sap production, thus reducing the ability of the tree to combat infestations (Tempireli *et al.* 2015). Forest disturbance modelling has shown that an increase in summer and winter droughts enables beetle populations to increase in size and distribution at an accellerated rate (Hart *et al.* 2017). This impact is compounded with increasing rates and severity of droughts in North America, Asia, and Africa, a phenomenon triggered by anomalies in seawater temperatures brought on by climate change that forces rainfall to happen over the seas instead of land (Dai 2011).

However, the idea of drought being the leading cause of spruce beetle outbreaks has been challenged and it is suspected that changing temperatures have more of an influence on beetle outbreaks than drought. It is thought that warmer temperatures allow the beetle to complete a reproductive cycle in one year instead of two or three and lowers the death rate over the winter (Tempireli *et al.* 2015; Pettite *et al.* 2020). Warmer temperatures mean that the initial temperature needed for release from overwintering diapause (16 degrees Celsius) is reached sooner in the spring and that the summer season tends to last longer (BC 2020). This allows the insects to obtain more resources and complete the less common one year cycle. The improved survival rates and faster reproduction cycles means that the populations can grow faster than ever, having a detrimental effect on tree populations. The effects of drought are not completely discarded and are usually thought of as a distant second cause of beetle population growth, with warming temperatures being the most prominent (Kolb *et al.* 2016; Pettite *et al.* 2020).

Additionally, but to a lesser extent, it is believed that favourable weather in recent years has created more storm events that facilitated forest disturbances (FNNRD 2018). Blown down trees create beetle habitat and allow for the spruce beetle populations to grow, thus creating a large enough population in the downed trees to then move to the standing trees when primary food sources diminish (FNNRD 2018). This accounts for some beetle populations growing in small areas but it does not account for the large-scale growth in population size (Pettite *et al.* 2020).

3.5.3 Effects of Tree Species Diversity

Stand diversity is pivital to the susceptibility of forest stands to insect attack. Insects will target monocultures or stands with lower diversity over diverse stands with multiple species with varying characteristics (Jactel *et al.* 2007; Walker 2012; Conner *et al.* 2014). This was investigated by Conner *et al.* (2014) where a multitude of factors in a variety of stand types was analyzed to determine if stand diversity affects beetle attack severity. The models indicated that elevation, heat index, stand diversity, and DBH all contributed to the survival of individual trees but having a diverse stand of non-spruce conifers had the greatest impact on beetle severity in the stand as a whole. It was theorized that the spruce beetles have a harder time finding spruce trees when spruce are intermixed throughout similar-looking trees. Another idea brought forward in the report was that the chemicals the beetles use to find spruce trees was interrupted by the chemical released by the other conifers, thus diluting the trail and making the location of spruce trees more difficult (Conner *et al.* 2014).

Another hypothesis for why stand diversity helps mitigate the severity of spruce beetle attack relates to the ability of the stand to have larger amounts of biodiversity. The idea is that, as stand diversity increases, the area becomes more complex with different stand structures, allowing for different niche species to establish. This will then allow more generalist species to be present on the site, feeding on an array of other species. These generalist species can feed on the beetle when it is present, but still keep their populations stable when they are not present since there are other food sources (Jactel and Brockerhoff 2007).

4. MATERIALS AND METHODS

4.1 DATA COLLECTION AND PLOT LOCATIONS

Data collection via timber cruising was done in 2018 and 2020 in the Mischinsinlinka and Gaffney landscape units respectively. These landscape units are in the Omineca forest district, which is located just outside of Prince George, British Columbia (MAL 2008). Three stands were cruised in the Mischinsinlinka landscape unit and two in the Gaffney landscape unit. The stands in the Mischinsinlinka landscape unit were all located in the same valley and less than five kilometres from each other and the Gaffney blocks were spaced out over 10 kilometres. Table 1 gives the GPS locations of the first plot of each stand. Blocks beginning with MIS were located in the Mischinsinlinka landscape unit, while the blocks NAT001 and MK033-1 were located in the Gaffney landscape unit.

Table 1. UTM coordinates for primary plots.

GPS location of the first plot of each stand		
block	easting	northing
MIS001	1199258	1149512
MIS036	1199685	1148377
MIS040	1200113	1150497
NAT001	455528	6124837
MK033-1	414881	6127150

The cruises were done as plot cruises with the use of basal area factors and digital tablets following the 2017 timber cruising manual (BC 2017). The tree species, count, and age, as well as the trees infested by spruce beetles and percentage of trees killed by spruce beetles for each plot, was entered into a spreadsheet. From these values, tree species composition, percent of spruce trees infested by beetles, and percent of spruce trees killed by beetles was calculated. Linear regression for DBH versus beetle kill severity, and tree height versus beetle kill severity was completed. Lastly, there was a logistic regression applied to the available data to determine the probability of a beetle attack on spruce for each landscape unit.

The age of trees was collected periodically following the cruising manual and cruise plan requirements. This means trees were aged if they were: over merchantable size, representative of their tree class, or were suspected of being a different tree class than they would traditionally be classified as based on physical characteristics. The tree age data was analyzed in a spreadsheet to look at the average, the maximum, and the minimum of each block and individual species.

4.2 THE AREA OF STUDY

The study area is located in the Omineca region of Northern British Columbia. This region contains a variety of landscape units, with the Mischinsinlinka and the Gaffney landscape units being the focus of this study. Their location can be seen on the map of landscape units in Northern British Columbia located in the appendix. These two areas were the focus of this study due to their designation as 'spruce beetle blocks' by the British Columbia government. Spruce beetle blocks are areas of forest that have been killed off by spruce beetle and need to be harvested because of fire risk and potential loss of fibre for the forest industry (FNNRD 2017). These areas of forest were chosen because they are all present in the BEC (Bio Geo-climatic Ecosystem Classification) zone SBS (Sub-boreal Spruce) and have overlapping subzones vk. BEC zone SBS has a variety of environmental conditions in it and it most notably dominated by lodgepole pine and sub-alpine fir. Spruce species make up a small percentage of tree speices in the area, but the wet and cool subzone of vk allows for their dominance in some areas (UBC 2020).

5. RESULTS

For ease of use and data entry, tree species were shortened to two-letter abbreviations. Hybrid spruce is represented by sx, balsam fir and subalpine fir as bl, lodgepole pine as pl, and trembling aspen as at.

5.1 BASIC STATISTICS

The extent of spruce beetle damage can be seen in Table 2, it depicts how all the blocks in the Mischinsinlinka landscape unit had between 37% and 47% of all spruce trees surveyed show signs of beetle attack and over 90% of these trees dying due to the beetle. The Gaffney landscape unit blocks faired much better, with both blocks having less than 10% of their spruce showing signs of beetle attack. Block NAT001 had 100% mortality while MK033-1 had only 64% mortality.

Table 2. percent infestation and mortality of spruce.

block	% sx Infested by beetle	% sx killed	% sx Infested and killed
MIS001	46.88	46.88	100.00
MIS036	37.50	33.93	90.48
MIS040	43.48	40.58	93.33
NAT001	5.26	5.26	100.00
MK033-1	8.00	5.14	64.29

Tree species composition, as seen in table 3, was consistent throughout all of the Mischinsinlinka landscape unit blocks, with approxiamtly 40% spruce and 60% balsam fir, while The Gaffney landscape unit had a diverse composition of tree species between the blocks consisting of spruce, balsam fir, and lodgepole pine with aspen making up a proportion too small to consider in block MK033-1.

Table 3 shows that most blocks had fewer than 200 trees, but MK033-1 had 350 trees. MIS001 had the least number of trees (73).

Table 3. Percent and count of tree species composition.

Tree species composition (count)					
Species	MIS001	MIS036	MIS040	NAT001	MK033-1
sx	32	56	69	57	175
bl	41	80	115	29	157
pl	/	/	/	32	15
at	/	/	/	0	3
total	73	136	184	118	350
Tree species composition (percent)					
Species	MIS001	MIS036	MIS040	NAT001	MK033-1
sx	44	41	38	48	50
bl	56	59	63	25	45
pl	/	/	/	27	4
at	/	/	/	0	1
total	100	100	100	100	100

The average age of all species in all blocks was between 100 and 175 years, with maximum and minimum ages varying greatly, as seen in Table 4. Spruce trees in each block averaged between 100 and 200 years old while balsam fir ranged between 90 and 170 years of age. Only one lodgepole pine was aged in this study and it was 207 years old. No aspen trees were aged.

Table 4. Statistics of tree species and ages bly block.

Species		MIS001	MIS036	MIS040	NAT001	MK033-1
sx	average	198	142	146	102	156
	min	194	127	84	58	133
	max	202	157	248	162	171
	average	157	93	124	167	149
bl	min	121	77	56	158	106
	max	190	125	166	178	196
	average		/		207	/
pl	min				207	
	max				207	
	average			/		
at	min					
	max					
block	average	174	113	131	125	152
	min	121	77	56	58	106
	max	202	157	248	207	196

The heights and DBH measurements across the sites varied greatly between individual trees from 4.3 m to 40 m in height and from 12 cm DBH to over 50 cm DBH. This data can be found in the Appendix. The average DBH measurements for each site is shown in Figure 4, it can be seen that the MIS blocks had an average DBH between 40 and 50 cm while the GAF blocks had averaged between 30 and 40 cm DBH.

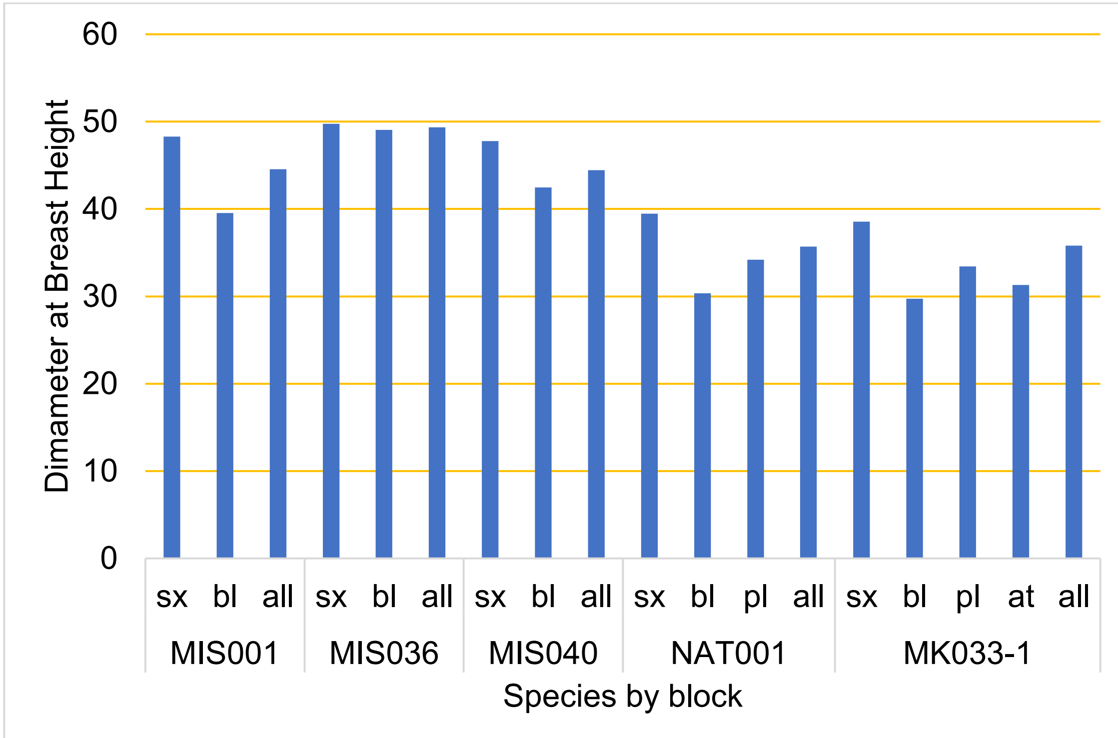

Figure 5. Average DBH by tree species in each block.

The tree heights on each site can be seen in figure 5 below, where it shows how the average tree heights between all blocks were similar. Analysis of the data shows that the average heights varied by 5.4 m between all species in all blocks.

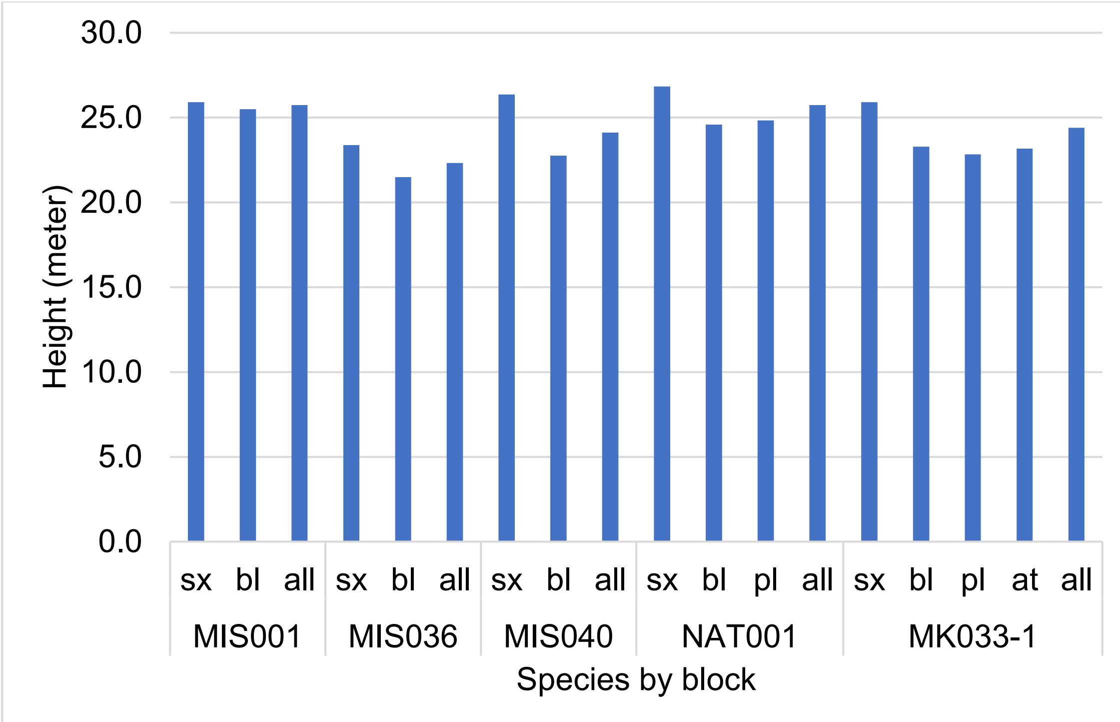

Figure 6. Average height of by tree species in each block.

5.2. LINEAR REGRESSIONS

Linear regressions between the severity of the beetle attack, DBH and heights of spruce trees were completed and depicted in figure 6 and 7. When DBH height was compared using linear regression, adjusted R-square values were low in all blocks, indicating weak connections (figure 6). The p-values in all but one of the blocks were above 0.05, indicating that these values found from the regression are not trustworthy. The adjusted R-square values (Figure7) shows a stronger correlation between height and beetle attack severity in the MIS blocks than in the GAF blocks. While the MIS001 and MIS036 block in the DBH vs mortality regression had a p-value of 0.001 and 0.055, respectively. This makes them the most significant results.

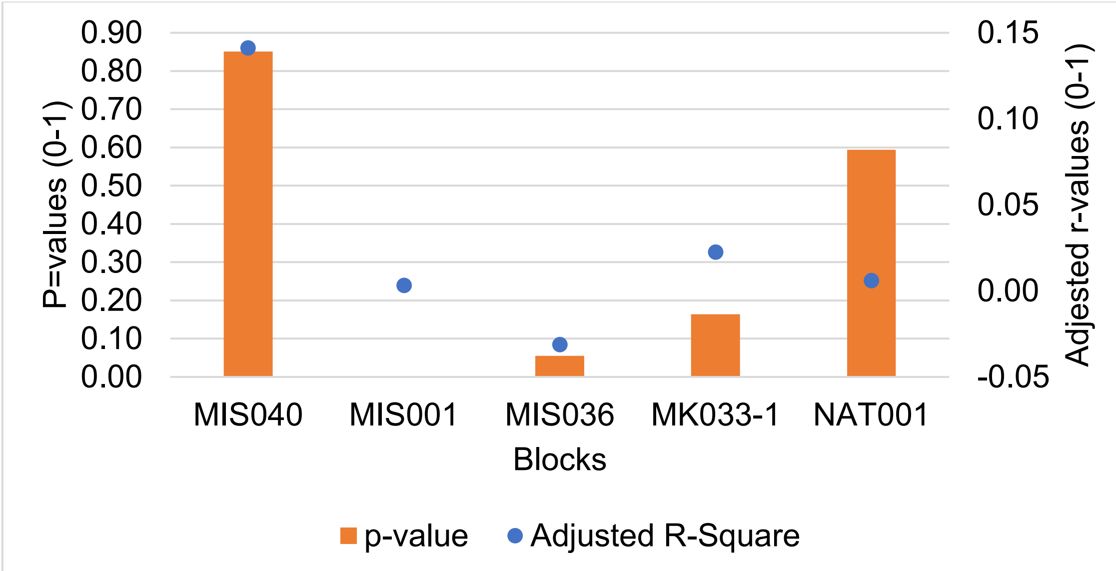

Figure 7. Linear regressions between spruce beetle kill serverity and tree DBH.

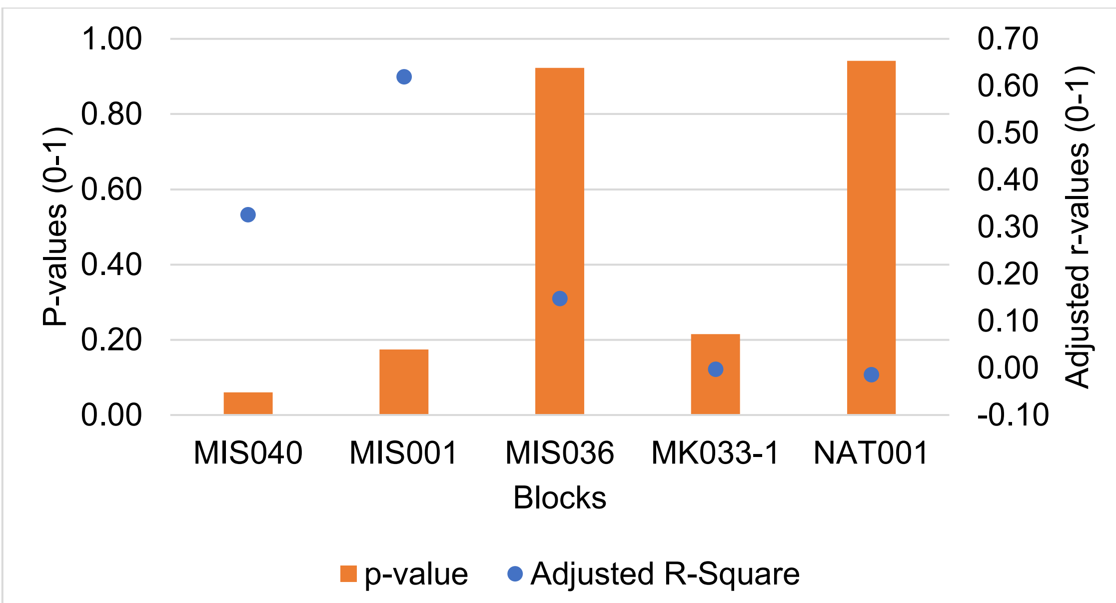

Figure 8. Linear regressions between spruce beetle kill serverity and tree height.

5.3. LOGISTIC REGRESSIONS

A logistic regression equation was applied to the available spruce tree data to evaluate the probability of a tree being killed by spruce beetle based on its height and DBH. The results, shown in figure 8, indicate that there is a much higher probability of a tree being killed by a beetle in the MIS blocks.

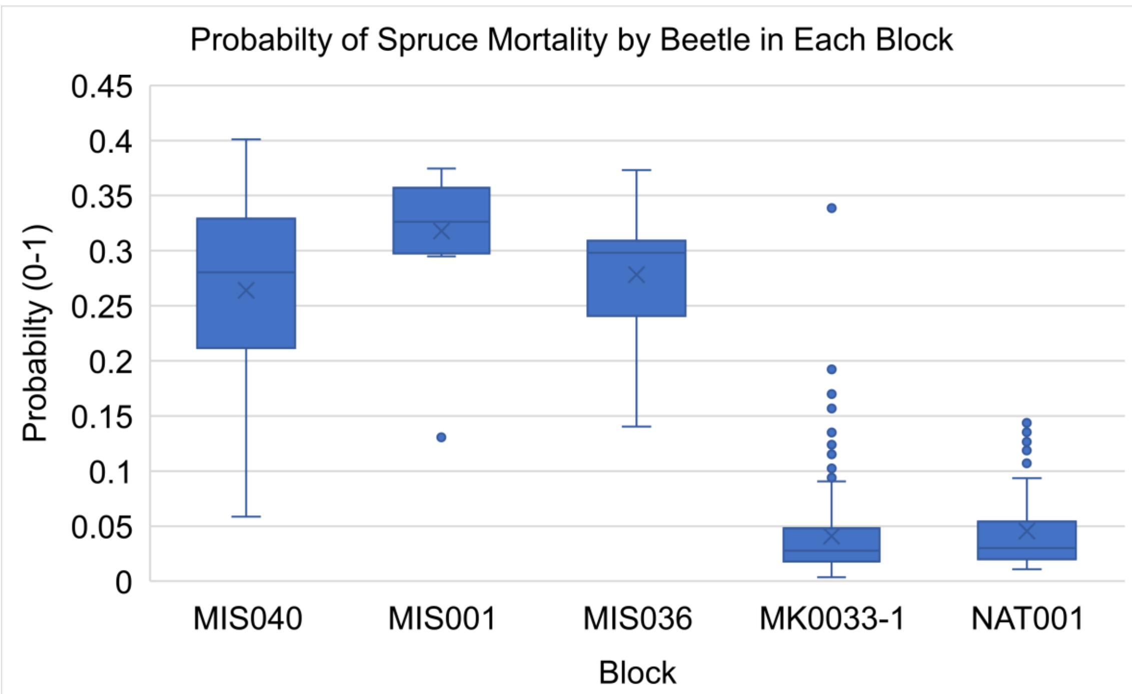

Figure 9. Probability of spruce mortality by beetle by each block.

6. DISCUSSION

6.1. FINDINGS

The results from this study show that tree species composition plays a larger role in predicting the severity of spruce beetle damage than host tree diameter or height. It was also found that the correlation between tree size and beetle damage is less strong in more diverse stands. Combining these two findings suggests that it is possible to create a more spruce beetle-resistant forest that produces higher quality timber.

The probabilities given by the logistic regressions show a clear distinction between the diverse Gaffney blocks and the less diverse Mischinsinlinka blocks. There was a higher probability, on average, in the Mischinsinlinka blocks of a tree being attacked than in the Gaffney area, with the average probability of tree mortality attributed to the spruce beetle being 4.2% in the Gaffney and 27.9% in the Mischinsinlinka. This falls in line with the findings of Conner *et al.* (2014) and Six and Bracewell (2015) that indicate that a species-diverse stand can reduce insect predation. Both sites had similar tree heights ,and it can be argued that tree species diversity plays a more important role than tree height when predicting spruce beetle attack rates. The average DBH, however, varied by nearly 20 cm between the MIS and GAF landscape units. The DBH could be a confounding variable since it is believed that DBH, alongside height, is one of the key indicators for spruce beetle susceptibility (Six and Bracewell 2015).

The linear regressions present a good indication of how the spruce beetle works in both diverse and non-diverse stands. The data suggests that height and DBH play an important role in predicting the effects of the spruce beetle in less diverse stands, but less so in more diverse stands. Higher R-values found in the regression of height versus beetle kill severity were found in the less diverse Mischinsinlinka blocks with the opposite being true in the Gaffney blocks. Building on the ideas discussed in Conner *et al.* (2014), this could be because of the availability of resources for the beetle. When there is a greater variety of host trees available to beetles, it is more likely that larger trees will be predated over smaller ones. In a less diverse stand, the size of the tree plays less of a role since the beetle has fewer options and must use whatever tree is available.

It should also be noted that both the MIS and GAF landscape units had around 40% and 50% spruce in their species composition, respectively, and the GAF landscape unit only had one additional coniferous species making up 10% to 30% of the species composition. This suggests that even having one additional coniferous species on the site could vastly improve how a forest resists a spruce beetle outbreak and increase the yield of desired species. When combined with the lower correlation between tree size and beetle damage found in more diverse stands, this could result in higher yields of timber with higher quality if stands are planted with multiple coniferous species.

The presence of deciduous tree species on the GAF landscape unit seems to have had little effect on the susceptibility of the stand to spruce beetle since it made up less than 10% of the sites in the GAF landscape unit. This supports previous literature discussed in this thesis.

6.2. APPLICATION OF FINDINGS

The findings of this thesis, along with other publications about spruce beetle, can have important implications for spruce forest management practices. When applying this knowledge to real-world scenarios, it can be used to predict spruce beetle outbreaks and give recommendations for silvicultural practices. This is because models with this information can i) determine the probability of a site being attacked ii) be used to determine the maximum yield of a site with minimal risk of insect infestation, and iii) help in selection of species composition in silvicultural practices to prevent beetle infestation in the future.

The information found in this thesis can also be used to determine the probability of a site being attacked by spruce beetle based on average tree height, DBH, and site species composition. This is important information relevant to forest management activities because it can prioritize high-risk areas of available harvest areas. Prioritizing high-risk areas can limit the number of available resources for the spruce beetle during population peaks, resulting in lower beetle numbers overall.

The findings in this thesis can also be used to predict the maximum yield of a site concerning the probability of spruce beetle attack. Knowing that height and DBH play an increasingly important role as a stand's average height and DBH increases means that it is possible to predict the maximum yield of a site before it becomes too much of a risk concerning spruce beetle susceptibility. If a site has low tree species diversity and is dominated by spruce, it will have a high likelihood of being attacked by spruce beetles during an outbreak year. If a stand has low tree species diversity and a small average height and DBH, it will probably not be attacked by spruce beetles and can continue to grow.

These findings could also help choose tree species composition in silvicultural practices to prevent spruce beetle infestations in the future. Conner *et al.* (2014) discusses how more coniferous species on a site helps reduce the severity of spruce beetle attack, and Temiperli (2005) discusses the eventual loss of spruce biomass in forests due to climate change (Conner *et al.* 2014, Temiperli 2015). Therefore, planting a more diverse block would be anvantagous for forestry companies when planning and approving silvicultural practices. With an expanded supply of data and a more in-depth analysis, it is possible to predict the optimal tree species composition of a site to minimize tree mortality on a site due to beetle kill. The effects of this research on volume and wood quality should be further investigated, but that is beyond the scope of this thesis.

Planting more diverse tree species in stands may not only be beneficial economically in terms of timber production, but it may also be emulating what future forests will eventually look like. The rise in temperatures and drought conditions have created favourable conditions for the beetle, and this trend is expected to continue (Conner *et al.* 2014; Temiperli 2015). A model done by Temiperli (2015) predicts that climate change will eventually create an environment that supports more lodgepole pine and Douglas-fir (*Pseudotsuga menziesii*) and less Engelmann spruce. This could result in large areas of spruce being affected by spruce beetle, especially if blocks are planted with mostly spruce. Planting more diverse tree species can be an option to help forests adapt to conditions brought on by climate change and to help mitigate the effects of spruce beetles.

6.3. ADDRESSING PROBLEMS

Multiple problems occur in a limited study like this one. There were only five blocks under study; each with a limited number of tree species, age classes, and ecosystem types. If this study was to be continued or repeated, there should be an effort to include more diverse areas that have a variation in elevation and tree species type.

Since this data is coming from timber cruising surveys that were completed on areas for harvest, there is a bias to be addressed. The areas being surveyed are meant for harvest, meaning that it ignores other areas that are inaccessible or non-profitable. This in turn means that there is not an even assessment of age classes and diameter classes since areas for harvest will logically be mainly in areas of high-value species and diameter classes. Further bias is present when one considers that the blocks for harvest were given under the pretense that they were fully attacked by the spruce beetle. This means that areas close to the blocks could theoretically have the same composition but be ignored if they did not have enough beetle damage.

Additionally, there was no effort made to see what species of invertebrates were present on the sites. As stated by Jactel *et al.* (2017), the diversity of organisms on a site could help keep beetle populations in check. If there was a difference in biodiversity between the sites, that would be a factor not accounted for and bring the value of the conclusions into question.

The statistical analysis of the available data came up with a variety of issues, mainly based on the disproportionate number of data points available on spruce trees at each block. Blocks MIS040, MIS001, MIS036 had 43, 16, and 28 data points respectively while blocks MK03301 and NAT001 had 175 and 57 data points respectively. This means that the MIS landscape unit had 87 data points while the GAF landscape unit had 232 data points related to spruce trees. This distribution of data resulted in unbalanced and non-homogenous statistical results, and so the findings of this thesis should be viewed with those limitations. Additionally, all but one of the blocks had a p-value for the linear regressions above 0.05. This indicates that the correlations from the majority of linear regressions were weak. This argues for the need to gather more data of more diverse types of stands to further support the findings of this thesis and gain statistical soundness.

7. CONCLUSION

The spruce beetle is a native species to Canada and naturally works in outbreak cycles. Paired with the blue stain fungi that they carry, these insects have the potential to kill large swaths of forest stands. These outbreak cycles will only worsen as climate change makes their forest habitats drier and, with warmer temperatures, enables shorter reproductive cycles. Current management of the spruce beetle uses a variety of short-term solutions that include traps, pre-emptive harvesting, and insecticides. Planting more diverse stands could be a strong tool to more effectively manage spruce beetle populations. Previous observations and models show how effective a diverse stand can be in resisting spruce beetle infestations, and the findings of this thesis support those observations. Combining previous findings and those of this thesis, it can be concluded that having more tree species diversity in a stand can mitigate the affects of a spruce beetle infestation. This thesis also concluded that tree height and DBH are useful tools in predicting spruce beetle attack, but only if the stand is low in tree species diversity and is susceptible to beetle attack. The potential outcomes of these results are revised silvicultural practices, with prescriptions for more diverse plantings becoming more common and more accurate pre-emptive harvesting.

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APPENDICES

This appendix consists of additional used in this thesis, as well as examples of maps of the area and the cruising cards used to assess the forests. The tables for basic statistics on tree DBH and height can be found here, as well as a completed cruise card. The crusing card has been partially covered at the request of Idustrial Firest Service to preserve privacy of the cruiser and the client.

APPENDIX 1. Linear regression results for DBH and Height.

Linear regression results for DBH							
block	Multiple R	R Square	Adjusted R Square	Standard Error	sig f	p-value	Observations
MIS040	0.402	0.162	0.141	0.447	0.008	0.851	43.000
MIS001	0.264	0.070	0.003	0.250	0.324	0.001	16.000
MIS036	0.083	0.007	-0.031	0.483	0.675	0.055	28.000
MK033-1	0.168	0.028	0.023	0.219	0.219	0.164	175.000
NAT001	0.154	0.024	0.006	0.225	0.253	0.594	57.000
Linear regression results for height							
block	Multiple R	R Square	Adjusted R Square	Standard Error	sig f	p-value	Observations
MIS040	0.585	0.342	0.326	0.396	0.000	0.060	43.000
MIS001	0.803	0.645	0.619	0.154	0.000	0.175	16.000
MIS036	0.423	0.179	0.148	0.439	0.025	0.923	28.000
MK033-1	0.058	0.003	-0.002	0.222	0.222	0.215	175.000
NAT001	0.060	0.004	-0.014	0.227	0.656	0.941	57.000

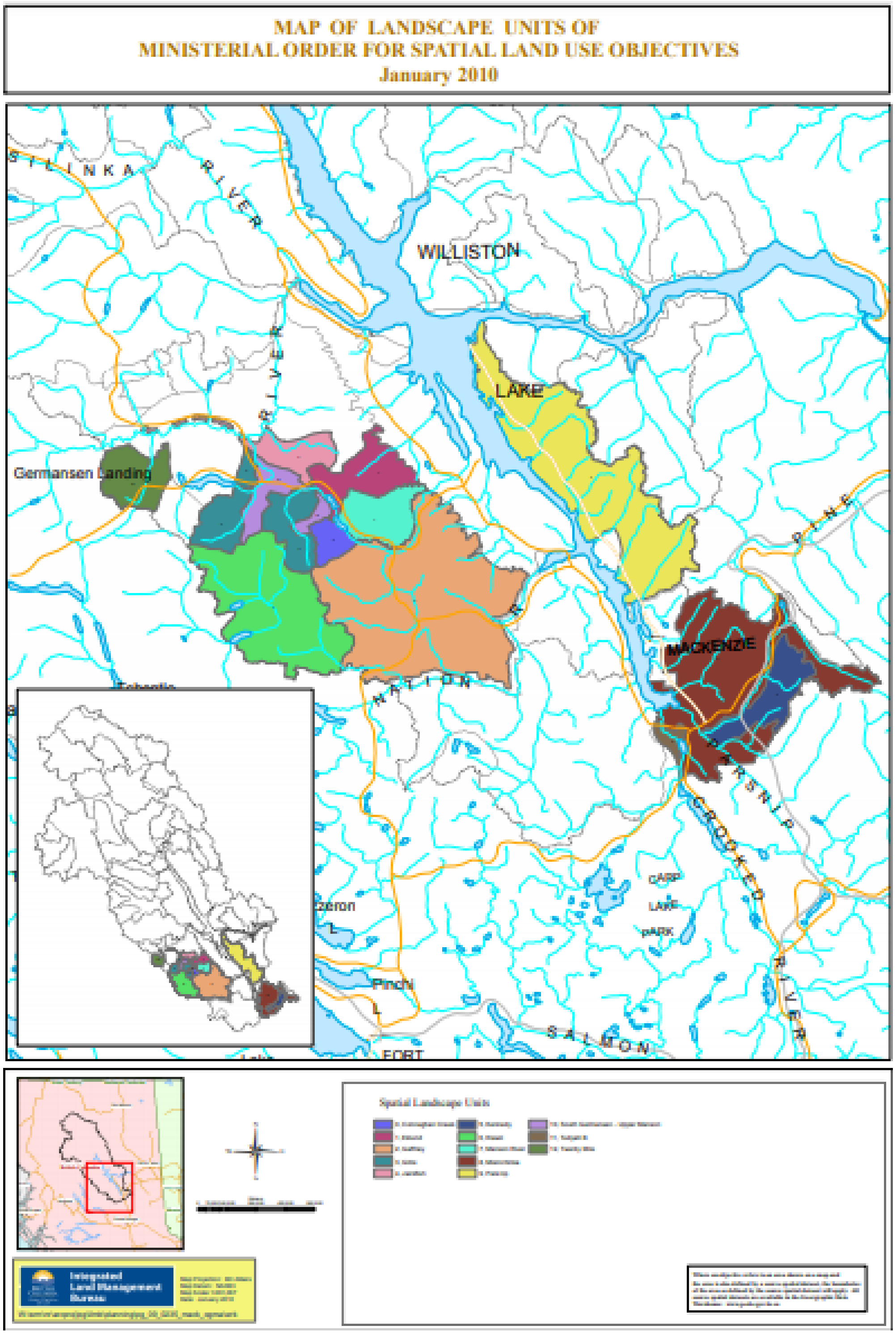
APPENDIX 2. DBH statistics by block.

DBH				
Block	species	min	Max	Average
MIS001	sx	22.8	73.3	48.3
	bl	28.3	51.9	39.55
	all	22.8	73.3	44.55
MIS036	sx	23.8	95.0	49.7
	bl	24.9	75.9	49.1
	all	23.8	95.0	49.4
MIS040	sx	21.6	77.9	47.8
	bl	16.9	85.6	42.5
	all	16.9	85.6	44.5
NAT001	sx	18.1	63.1	39.5
	bl	16.2	45.3	30.4
	pl	18	54.5	34.2
	all	16.2	63.1	35.7
MK033-1	sx	18.3	71.5	38.6
	bl	21.8	39.9	29.7
	pl	18.2	65.1	33.4
	at	25.2	35.0	31.3
	all	18.2	71.5	35.81857
min		16.2	35	29.74
max		28.3	95	49.73214

APPENDIX 3. Height statistics by block.

HEIGHT				
Block	species	min	max	average
MIS001	sx	4.3	33.0	25.9
	bl	17.4	30.8	25.5
	all	4.3	33.0	25.7
MIS036	sx	5.3	35.2	23.4
	bl	3.1	32.0	21.5
	all	3.1	35.2	22.3
MIS040	sx	5	35.1	26.4
	bl	3.9	35.1	22.7
	all	3.9	35.1	24.1
NAT001	sx	3.6	41.6	26.8
	bl	11.5	35.4	24.6
	pl	13	36.8	24.8
	all	3.6	41.6	25.7
MK033-1	sx	14.1	34.6	25.9
	bl	7.6	29.1	23.3
	pl	11	35.5	22.8
	at	20	26.1	23.2
	all	7.6	35.5	24.39171
min		3.1	26.1	21.49722
max		20	41.6	26.83684
difference		16.9	15.5	5.33962

APPENDIX 4. Maps of the area.



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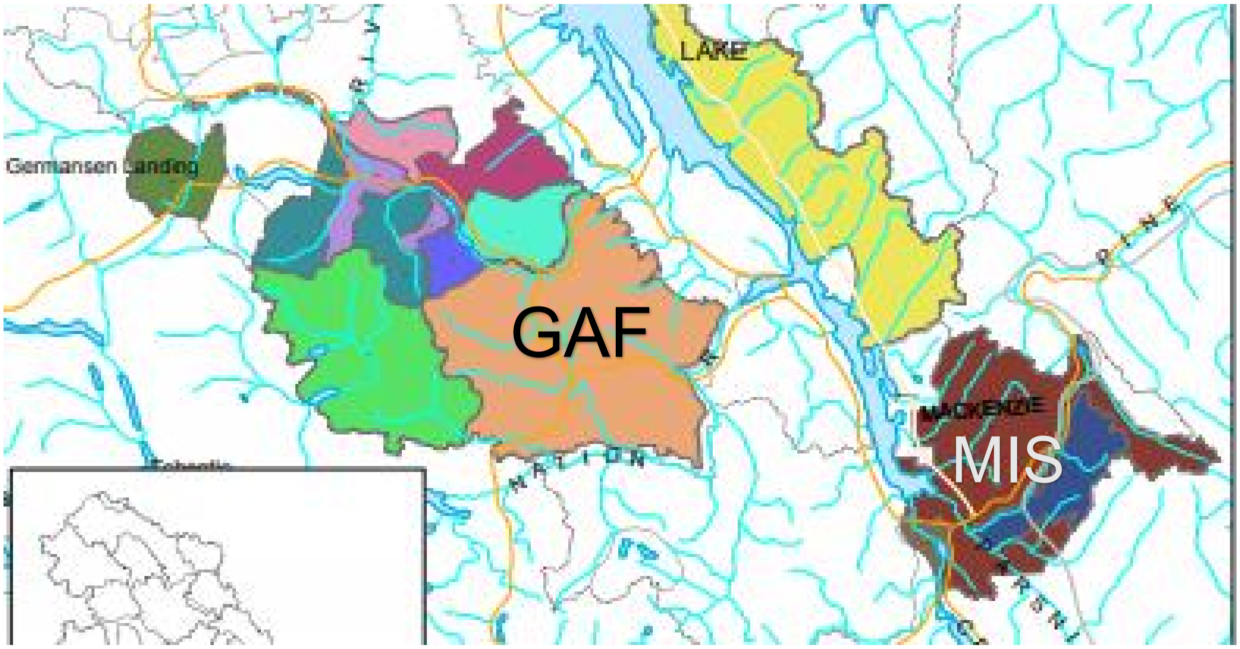

MIS

APPENDIX 5. Example cruise notes.

License	CP	Block	Strip	PLOT #	O/C	Type	Age	Height	M/C/S
[redacted]		001	1	2	O	1	11	19	M

Hectares	BAF	F/H/B	DBH Lt.	Harvest	Slope %	Bearing	Plot Centre From RT
0.000	8.000	F	12.5	SC	17	101	2.73m @ 230°

					Path Remarks										Dam.			Quality Remarks								Age				Borderline Trees						Walk	
Tree #	Height	Species	DBH	Tree Class	Cork	Blind Cork	Scar	Fork/Crook	Frost/Crack	Mistletoe	Rd/Branch	D/B Top	Selective	Root Rot	Insect	Fire	Blow Down	Spiral Grain	Sweep	Lean	Live Limb	Stub	1st	2nd	Crown Class	Counted	Correction	Total	Maturity	Slp Dist	Slope %	F/C	Min. DBH	In/Out	Bearing	Distance	Bearing
1	13.0	PL	18.8	5			1																						M								
2	23.5	SX	29.3	1																									O								
3	14.8	SX	20.4	1																						72	19	91	O								
4	25.1	SX	36.5	2					1																				O								
5	16.6	PL	21.1	5			1										E												M								
6	18.6	PL	22.7	5													G												M	3.88	0	C	21.9	I			

tree 6 +6m to height estimated due to broken top leaning in another tree
no signs of beetle in pine

Date:	9/21/2018
Cruiser:	[redacted]
Assistant:	
Assistant2:	
Endorser:	
Big BAF:	
Ecosystem:	
Snow Depth:	
Map #:	
Photo #:	
Projection:	0
UTM Zone:	0
Plot East:	[illegible]
Plot North:	[illegible]

Signed:

[redacted]

Plot Location: SL 0+m @ °, 0+m @ ° From

PRP: 10.86m @ 018 to PC, East: 455524.983 North: 6124927.039 Sats: 10 PDOP: 2.2 UTC/GMT: 16:20:56

CruiseMate™ PC 2018 5.1.3.0

License	CP	Block	Strip	Plot	OC	Type	A10	HT	MC	Main Area	Main BAF	Main FH	Main DBH	Sub Area	Sub BAF	Sub FH	Sub DBH	HM	Slp %	Slp Brg	Yr	Mn	Dy	PRP Dist	PRP Brg	Ref Dist	Ref Brg	Null Plot	100%	Big BAF	Drop Plot
[redacted]		036	01	3	O	4	11		M		10.000	F	12.5					CC	50	280	2020	08	09	5.77	227	1.95	22	☐	☐	☐	☐

TREE DETAILS

#	W	HT	SP	DBH	TC	MS	LD	CK	BC	SC	FO	FR	MT	RB	DB	SG	LN	SW	LL	ST	K1	K2	SE	CC	LC	RR	IN	FI	BD	SD	S%	FC	Min DBH	CTD	COR	TOT
1		24.4	BL	54.2	7																						3									
2		24.2	SX	41.6	7			1							1												7		E							
3		8.5	SX	60.8	4																															
4		20.0	BL	48.4	7																															

SKETCH

ALPHA LOG GRADES

<None>

USER LOG GRADES

<None>

SAMPLE TREE DETAILS

<None>

NOTES

Tree 2: 4.8M STANDING HT
Tree 2: 19.4m on ground
Tree 3: Top rotten

Location

Projection	BC Albers	Easting	1199565
UTM Zone		Northing	1148497

BEC

Zone
Sub Zone
Variant

FIZ

FIZ
Unit Type
Unit Num

Species Composition VC Age SI

Map Sheet #
Photo #
Forest Cover
Snow Depth (cm)