BLACK SPRUCE ALTERNATIVE SILVICULTURAL METHODS AND DWARF MISTLETOE IN NORTHERN MINNESOTA, USA

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Raychel Hana Skay

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Dr. Marcella Windmuller-Campione

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Chapter 1: Introduction.

Black spruce (*Picea mariana*) is a common tree across the northern forests in North America extending across Canada and the northern United States from Maine and Labrador to Alaska and British Columbia. Its northern range extends to the northern tree line of the boreal forest and south to Minnesota, Wisconsin, and Massachusetts. Across its range, black spruce is an important species both economically and ecologically (Burns and Honkla 1990). The black spruce forest provides critical habitat for species such as the snowshoe hare (*Lepus americanus* Erxleben, 1777), spruce grouse (*Falcipennis canadensis* (Linnaeus, 1758)), American marten (*Martes americana* (Turton, 1806)), salamanders (Salamandridae family), cavity-nesting birds, and other small mammals (Cimon-Morin et al. 2010).

In Minnesota, black spruce comprises 648,000 hectares of the 7.04 million forested hectares in the state (Miles 2017). It is also the second most harvested species for pulpwood in Minnesota (Minnesota Department of Natural Resources 2017). Black spruce in Minnesota typically inhabits lower quality sites, primarily lowland areas in acid peat bogs and swamps. The historic disturbance regime for black spruce was high intensity stand replacing fires creating mostly even-aged stands. In the absence of fire, wind and disease create small to medium openings allowing the development of multi-aged black spruce stands.

Fire from both anthropogenic and non-anthropogenic ignition sources are now rare in lowland systems. The clear-cut silvicultural system attempts to mimic the stand replacing aspect of fire and is currently the most common silvicultural system followed by aerial seeding for black spruce in northern Minnesota. While the clear-cut system can mimic some attributes of a fire, there are some large differences that influence stand development (Rowe 2016). Hence it is important to understand how alternative silvicultural systems can influence stand development. Additionally, one of black spruce's most damaging disturbance agents, eastern dwarf mistletoe (*Arceuthobium pusillum* Peck; EDM), appears to have been historically decreased after high severity fires.

EDM is a native, parasitic plant that forms witches brooms in black spruce, reducing growth and eventually killing trees thus creating mortality circles. It is estimated that 11% to 50% of black spruce stands in Minnesota are infected with EDM (Baker et al. 2012). Stands infested with EDM have reduced regeneration success, reduced growth and yield, and increased risk of transitioning to non-forest brush lands or grasslands (Baker and Knowles 2004). However, there is limited research on the interaction between EDM and stand dynamics in black spruce. EDM has the potential to influence overstory and understory structure and composition potentially resulting in stands with different successional trajectories and influence both the economic and ecological benefits gained from the stands

This study has two main objectives. In Chapter 2 the purpose is to further examine the stand dynamics of three different silvicultural systems in black spruce in northern Minnesota. This study is a continuation of Anderson et al. (2018) and uses long-term data to quantify alternative silvicultural systems on stand development and growth. I have used a dendrochronological approach to understand stand development and growth over time in three different silvicultural systems: strip clear-cut, patch clear-cut, and shelterwood. The third chapter continues to explore stand dynamics and development in black spruce stands. The purpose of Chapter 3 is explore stand development under different levels of EDM. Finally, results from Chapters 2 and 3 will be summarized and will provide implications of future management in Chapter 4.

Chapter 2: Assessing the long-term growth response of black spruce in Minnesota to three different silvicultural treatments using dendrochronological methods.

Introduction

The black spruce cover type in Minnesota represents about 9% of forested land in the state (Miles 2017). Black spruce is second to aspen as the most harvested pulpwood species by volume (Minnesota Department of Natural Resources 2017).) The black spruce forest also provides habitat for many species including snowshoe hare (*Lepus americanus* Erxleben, 1777), spruce grouse (*Falcipennis Canadensis* (Linnaeus, 1758)), salamanders (Salamandridae family), and other small mammals (Cimon-Morin et al. 2010). This means that black spruce is not only important to the state economically but ecologically (Viereck and Johnston 1990).

Traditionally, the black spruce forest has been managed using even-aged systems, especially clear-cutting methods (Viereck and Johnston 1990; Youngblood and Titus 1996). After the harvest, prescribed fire (Johnston 1977) or scarification (Kolabinski 1991) often is used as the site preparation method. Unless a natural regeneration method was to be used, aerial seeding would be used to regenerate the stand (Weetman 1975; Johnston 1977; Groot 2002).

There has been some exploration in Canada regarding alternative silvicultural systems. Typically these systems take advantage of advance regeneration (Groot and Hökkä 2000). One such system is the shelterwood system. A shelterwood is a type of regeneration method where some residual overstory trees are left to moderate the understory and allow the next cohort of seedlings to develop. This method has been adopted in Quebec where uneven-aged stands have formed and advance regeneration is present (Groot 2002; Groot et al. 2005). In Northeastern Ontario advance regeneration is protected and used in combination with strip clear-cuts (Deans et al. 2003). Thinning has been shown as an intermediate treatment to increase net merchantable volume over unthinned stands (Soucy et al. 2012) and improve post treatment radial growth by 20 to 100 percent over pre-treatment growth (Vincent et al. 2009). In Minnesota, uneven aged methods have been used in poor sites where layering is common (Heinselman 1959; Johnston and Smith 1983). Partial cutting has been shown to increase diameter growth in both even and uneven aged stands. It is less uniform in uneven aged stands due to variability in stand density (Pamerleau-Couture et al. 2015). Partial selection cuts in black spruce in Minnesota have been shown to result in slow understory growth (Heinselman 1959) and concerns exist about its profitability (Groot 2002). However, there has been limited research exploring the growth response of black spruce to different silvicultural systems.

The objective of this chapter is to examine the growth response that occurred over the last fifty years using dendrochronological methods of black spruce to three different alternative silvicultural treatments: shelterwood, patch clear-cut, and strip clear-cut. The effects of these three treatments are well understood in other systems, however little research has been done and little is known how black spruce responds.

Methods:

In 1948 the Big Falls Experimental Forest was established for the purpose of silvicultural, harvesting and utilization and economic studies in lowland conifers (Minnesota Department of Conservation; USDA Forest Service 1948). The Compartment Study was established in the same year using different silvicultural treatments in black spruce. The six treatments installed were clear-cut strips, clear-cut patches, shelterwood, group selection, single tree selection, and a light thinning. There was also a control with no harvesting. The treatments were completed between 1948 and 1960 and were measured before treatment, about five years after, and about ten years after treatment. After ten years it was found that the greatest diameter growth occurred in the shelterwood system, the selection treatments, and the light thinning. All other treatments did not vary much from the control (Anderson 2018). About fifty years later the experiment was remeasured in 2017. Only three treatments remained with enough replicates: shelterwood, patch clear-cut, and strip clear-cut. It was found that the shelterwood treatment produced the greatest increase in individual diameter growth but it also had the greatest mortality and a negative stand-level basal area growth. The shelterwood also outperformed other treatments in terms of regeneration and species richness of woody understory species (Anderson 2018). In 2017 tree cores were collected from the three remaining treatments resulting in a total of six compartments. Two compartments each from different treatments, clear-cut patches, clear-cut strips, and shelterwood were sampled.

Field Methods

Tree cores were collected on a subset of the remaining compartments during the summer of 2017. Treatments sampled were the clear-cut strips, clear-cut patches, and shelterwood. Details on each of the treatments can be found in Table 2.1. In each plot, one dominant or codominant tree was cored; this resulted in a total 76 trees. Tree selected to be cored were judged to be a good representative of the stand. The trees were cored as close to the base as possible ~30cm, parallel to the ground, and attempted to reach the center pith. The cores were placed in a plastic straw and taped and marked with identifying information.

Table 2.1: Information on the three types of silvicultural treatments that remain at the BFEF compartment study. Increment cores were collected from each treatment.

Type	Treatment	Description	Measurement Dates				Treatment Dates			
Even-aged	Clear-cut strips	North-south cuts (two to three per compartment); 20-40 m wide beginning from east side; 3 to 4 cuts over 17 years to harvest entire compartment	1950	1956	1960	2017	1950	1961	1964	1967
	Clear-cut patches	Patches of any shape, 0.1 to 0.2 ha in size; 3 to 4 cuts over 17 years to harvest entire compartment	1950	1956	1960	2017	1950	1961	1964	1967
	Shelterwood	Cut from below to ~11.5 m^2 ha^{-1}, leaving strong and vigorous trees; residual stand removed ~10-years later, avoiding damage to understory	1951	1956	1960	2017	1951	1961	NA	NA

Lab methods

In the lab the core information was copied onto a wooden mount and the core was glued on to the mount using Elmer's glue taking consideration that the wood's grain was in a vertical direction. The core was then wrapped using twine to prevent any twisting or distortion of the increment core. Once dried the core was unwrapped and sanded using progressively finer grits (120-420) to expose the yearly growth rings. Each core was then dotted using the standard decadal dotting system (4 dots for a millennium, 3 every century, 2 every 50 years, and one every decade). Each core was labeled by compartment, plot, tree, and year. The cores were then measured using a Velmex (Velmex INC 2009) data recorder, binocular microscope, and software program J2x

(Voortech consulting 2008). Each ring was measured to the nearest 0.001mm. Once measured, the cores were then entered into COFECHA? (Holmes 1982) to ensure accurate crossdating.

Analysis Methods

TRADER (Altman et al. 2014) is an R package that allows the reconstruction of disturbances from tree-ring data. Of the four methods that TRADER uses to detect release (major and minor) and disturbance two were used in this research. The first being radial-growth averaging criteria and developed by Nowacki and Abrams 1997. The second being absolute increase developed by Fraver and White 2005. Default parameters within the tool were used.

Results:

The cores show that a release can clearly be seen in cores A & B for each treatment (Figures 2.1, 2.2, and 2.3) . This release occurs around 1950 when the first treatment was recorded to have taken place (Table 2.1). Core C for all three treatments (Figures 2.1, 2.2, and 2.3) established after the last treatment on record. It can be seen that there was comparatively less competition in the few decades after establishment compared to cores A & B in each treatment. In many of the cores growth restriction can be seen in the most recent decade or two.

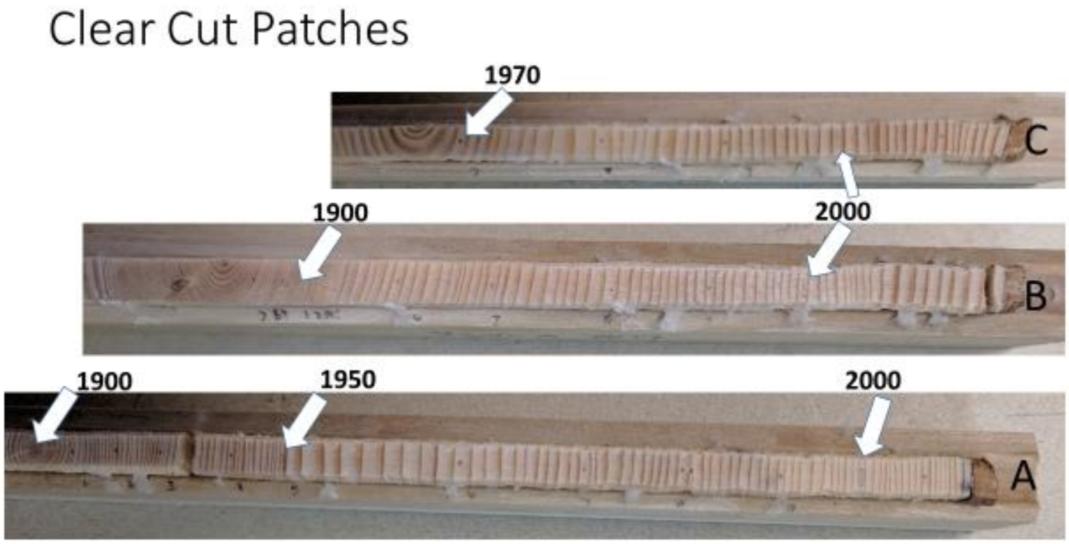


Figure 2.1: Images of three processed cores taken from the clear-cut patch treatment.

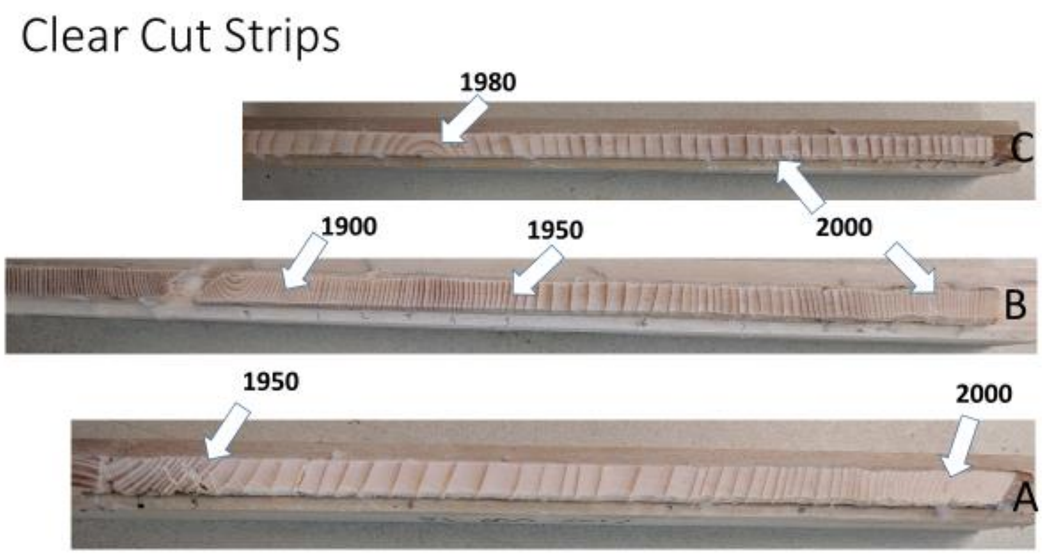


Figure 2.2: Images of three processed cores taken from the clear-cut strip treatment

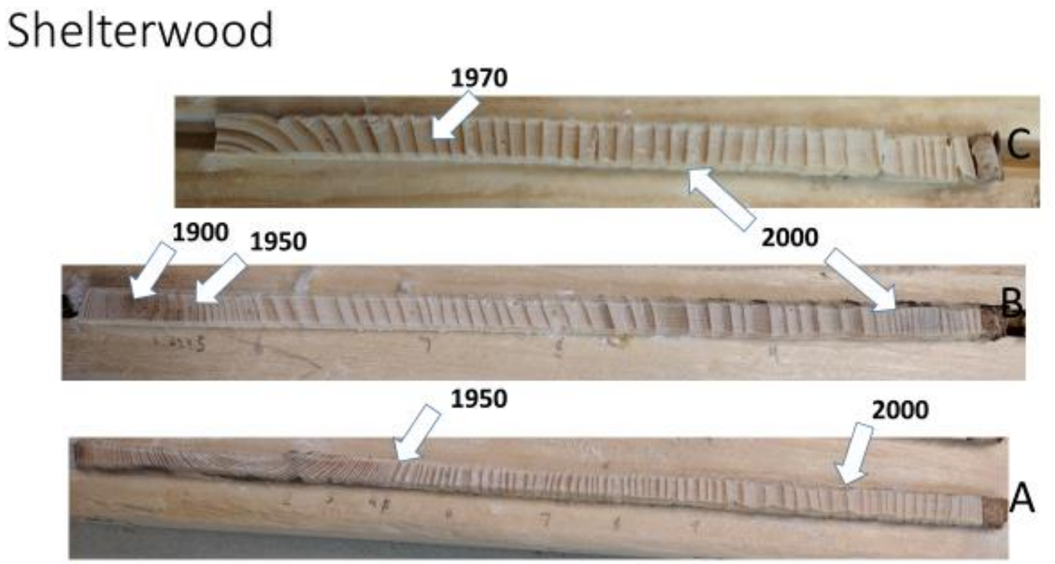


Figure 2.3: Images of three processed cores taken from the shelterwood treatment

COFFECIA Results

COFFECIA statistical program was used to assess the accuracy of crossdating. The series intercorrelation was found to be 0.437.

Table 2.2: COFECIA results by treatment.

	All Cores	Patch clear-cut	Strip clear-cut	Shelterwood
Number of cores	74	28	30	16
Oldest year	1863	1863	1890	1901
Intercorrelation	0.437	0.395	0.437	0.468

Shelterwood:

The Radial-Growth Averaging shows a significant release in 1950 (Figure 2.4) with over 50% of the trees showing the release. Using the Absolute increase method, many releases were detected in the 1950's and 1960's (Figure 2.5). For each release there was a greater percentage of trees showing the release with the absolute increase method. There were only 7 cores out of 16 that dated back before the first thinning treatment in 1951 (Table 2.1). The radial growth method detected more releases after the 1950 disturbance compared to the absolute averaging method.

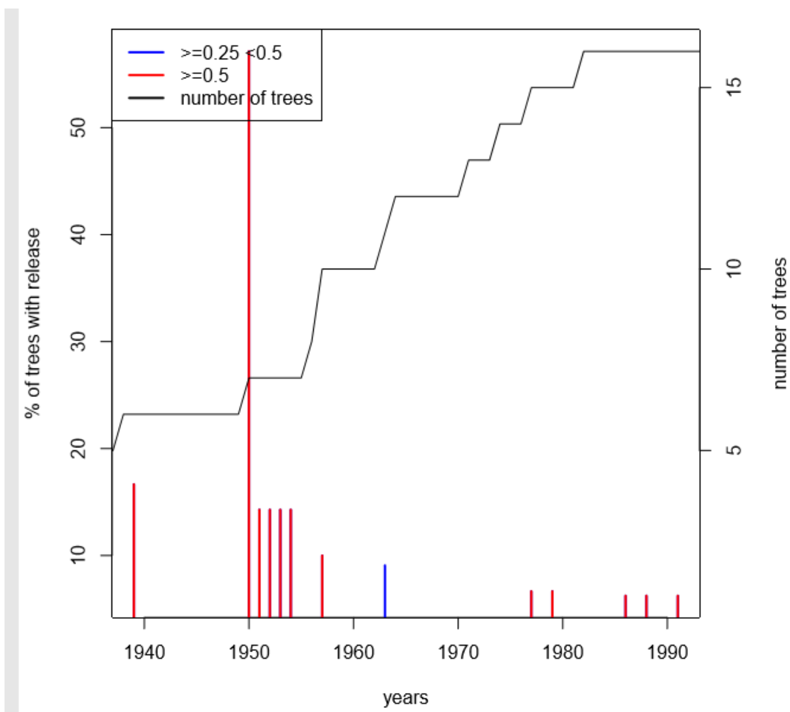


Figure 2.4: Radial Growth Averaging in the Shelterwood system. Red indicates a significant release. During the year 1950 a major release was detected in 1950 and over 50% of the trees recorded the release.

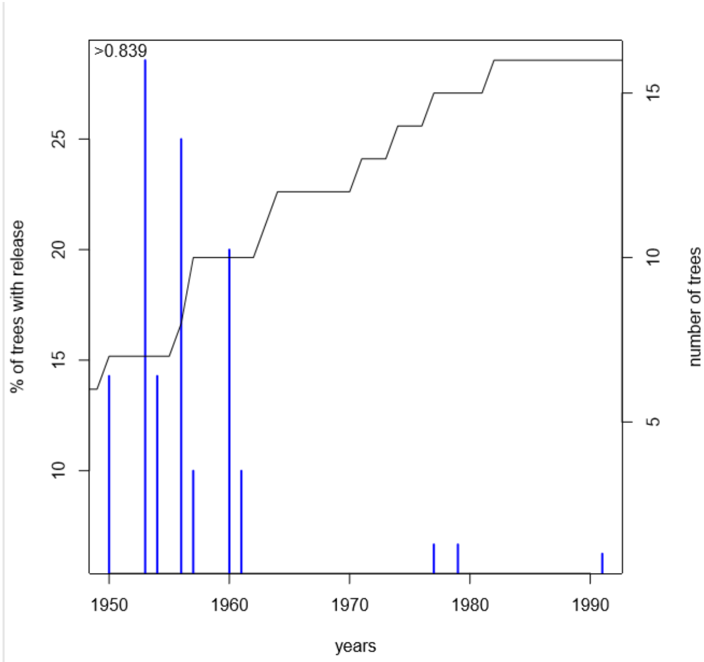
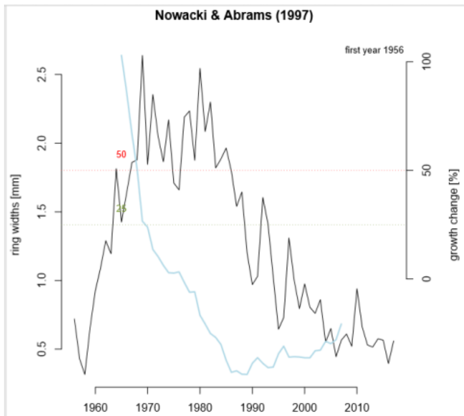
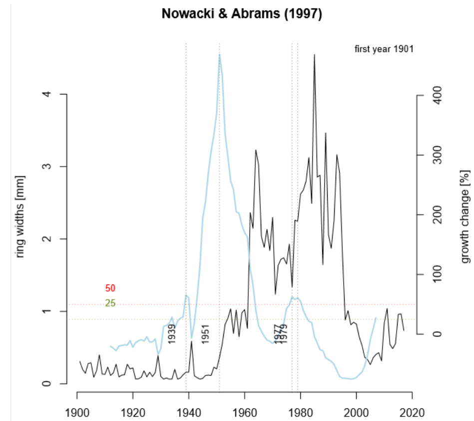
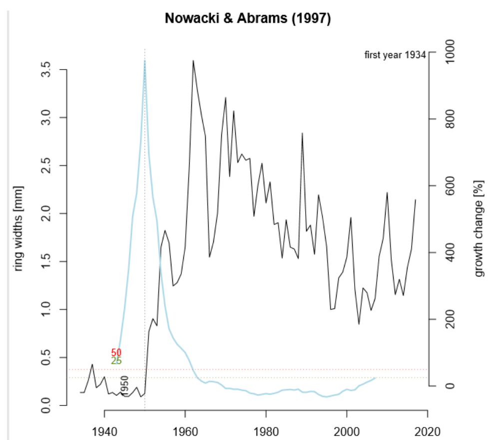


Figure 2.5: Absolute increase method. Many releases detected in 1950's and 1960's.

Three individual cores were examined to show tree level growth (Figures 2.6, 2.7, & 2.8). Figure 2.6 shows a core with a first date of 1956 showing a release in the early to mid-1960's. A treatment was completed in the shelterwood system in 1961 (Table 2.1). Figures 2.7 and 2.8 shows cores that established decades before the first shelterwood treatment and show a possible release in the early 1950’s the date of the first shelterwood treatment (1951) (Table 2.1). Figure 2.8 shows some other minor releases.







Figures 2.6, 2.7, and 2.8 (left to right): Individual core graphs show significant releases in the 1950’s with 2.8 showing significant growth soon after establishment.

Patch Clear-cuts

Of the 28 cores collected from the patch clear-cut system, only 7 established before the first treatment in 1950. Using the radial growth averaging there are many major and minor releases detected. Even before the first treatment in 1950 (Figure 2.9). Using the absolute average method fewer releases were detected (Figure 2.10). These all occurred in the 1950's and 1960's when all of the treatments were on record to have been completed.

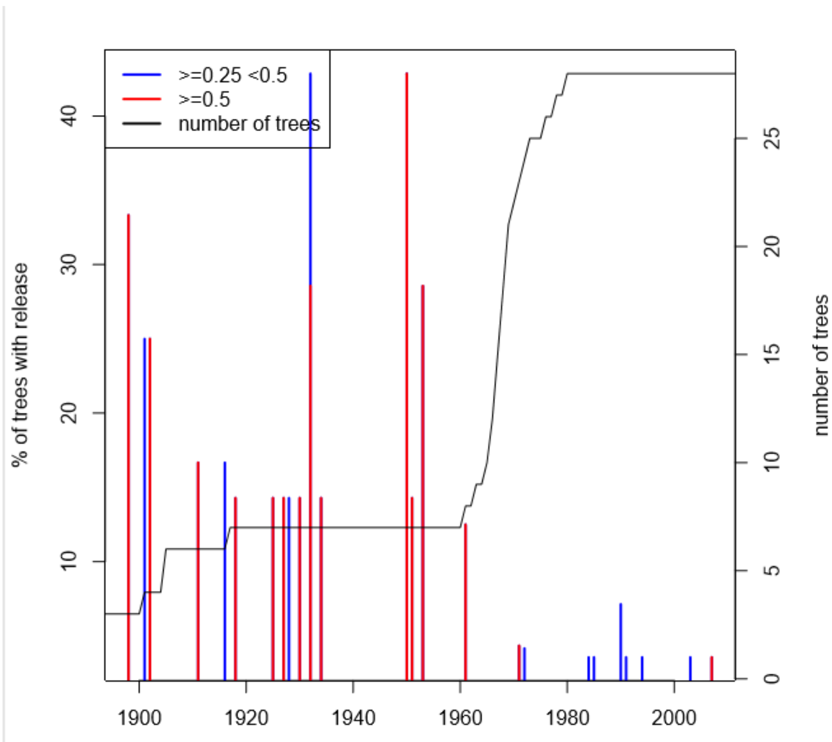


Figure 2.9: Radial Growth Averaging. Many disturbances detected before the clear-cut with significant releases in the early 1900's, 1920's and 1930's as well as the early 1950's and 1960's.

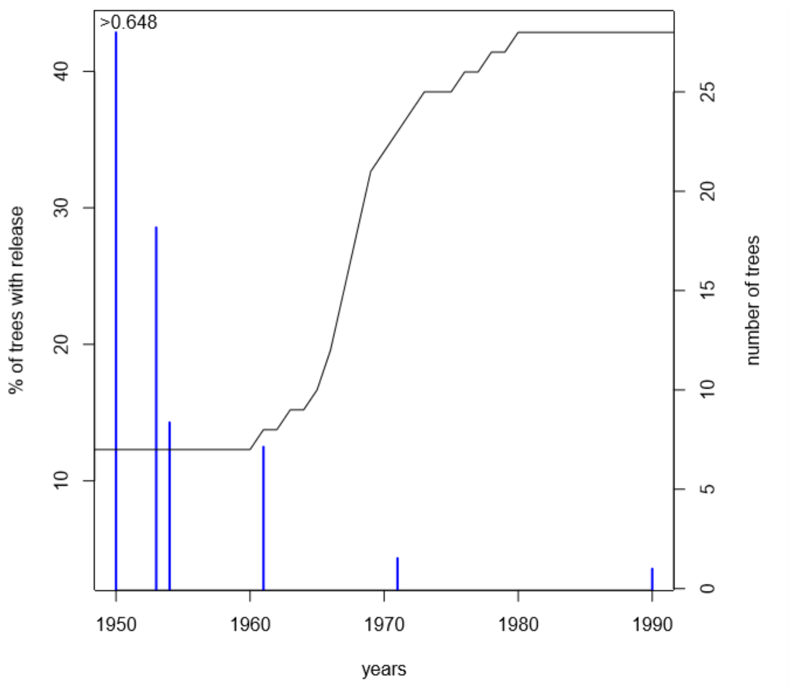


Figure 2.10. Absolute Increase. Releases shown in 1950's with one in early 1960's, 1970's, and 1990. These all occurred after or the same year as the first treatment in 1950.

Strip Clear-cut

Only 4 of the 30 cores taken from the strip clear-cut treatment established before the first treatment in 1950 (Table 2.1). Using the radial growth averaging method, major releases were detected in the early 1950's and 1960's with a lower percentage of the trees showing the release (Figure 2.11). Using the absolute increase method the releases that were detected occurred after the first treatment with many showing releases that could match with the treatment dates on record (Figure 2.12).

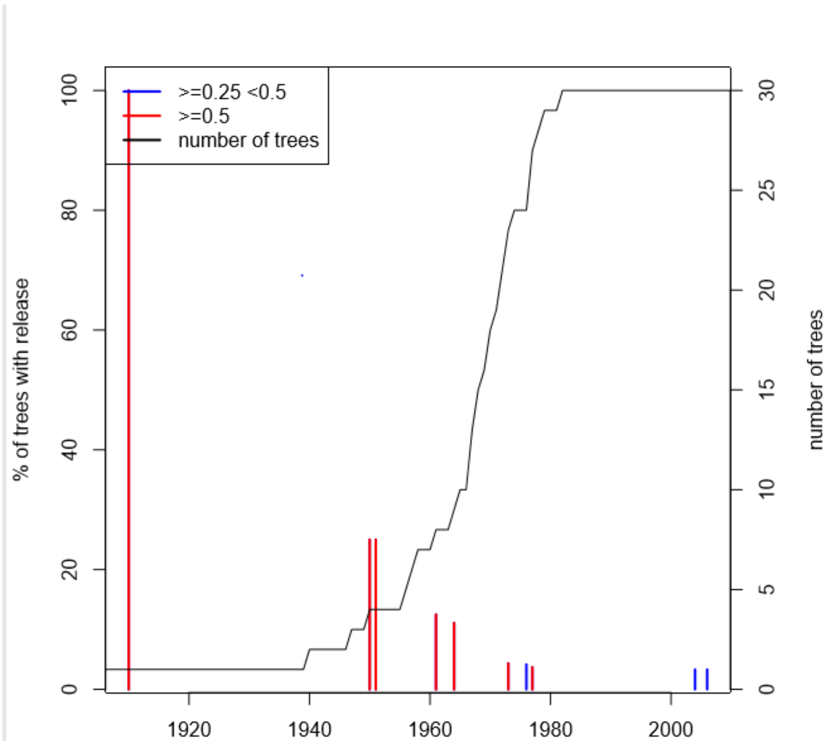


Figure 2.11: Radial Growth Averaging. Major release for one core in early 1900. Also major release in late 1940's and early 1950's and others in the 1960's.

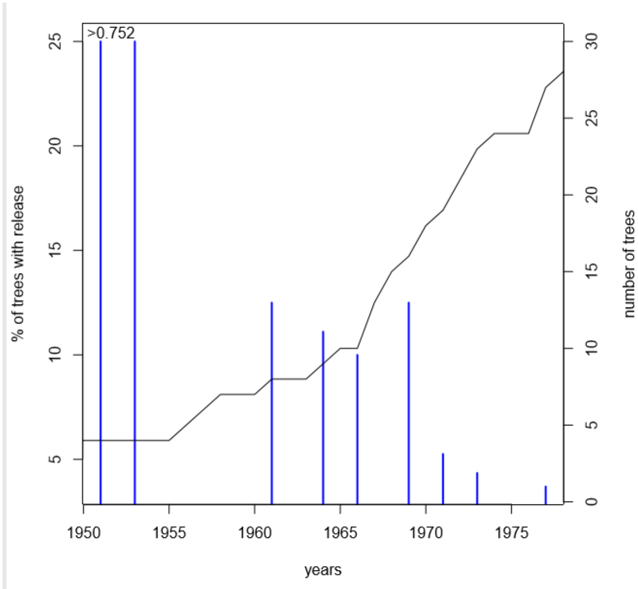
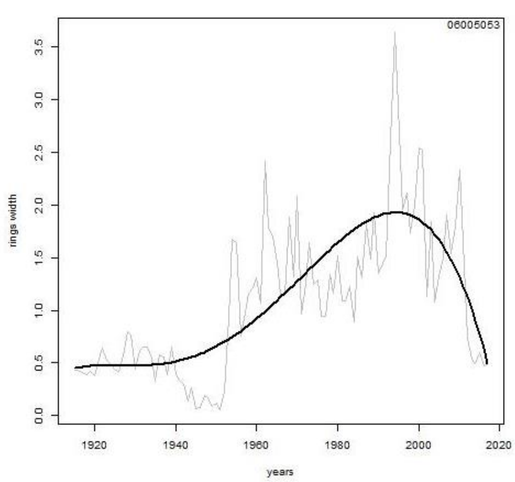
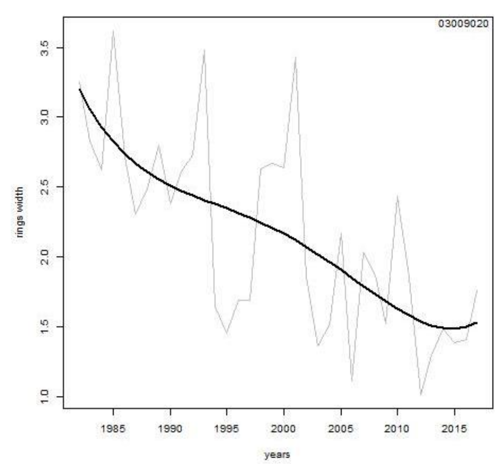


Figure 2.12: Absolute Increase. Releases detected in 1950's, 1960's, and 1970's. The strongest releases occurred in the 1950's in the 1 to 3 years after the first treatment.

Growth Modeling





Figures 2.13 and 2.14: 2.13 established before 1950 and 2.14 after. In 2.13 the growth trend shows a release beginning in the 1950's and then dropping off within the last two decades. 2.14 shows a declining growth rate since establishment.

Discussion:

Across all treatments in the Big Falls Experiment, black spruce has the potential to release and increase in growth when growing space is increased. Additionally, black spruce growth is influenced by density; as density increased after harvest growth rate decreased. The radial increase and the absolute increase methods both detected large releases during treatments years. However, there were differences in the number and the dates of those releases after 1960's. Trotsiuk et al. used TRADER (Altman et al. 2014) to compare four different methods of detecting past disturbances. They found that false positives (detecting a disturbance that didn't happen, type I error) were more common in forests with lower severity disturbances and that false negatives (missing a disturbance that occurred [type II error]) occurred more often in forests with a high severity disturbance (Trotsiuk et al. 2018). Of the four methods they compared it was found that the radial-growth averaging and absolute-increase methods had lower levels of type I and II errors (Trotsiuk et al. 2018). For this reason I selected the same two methods to look at the BFEF increment cores. It is noted that parameter settings do play a key role in the accuracy of reconstructing disturbance history (Trotsiuk et al. 2018). For this study the default parameters such as window lengths and release thresholds were accepted.

Research of this type has not been done before and the species autecology (mean growth rate, species sensitivity, and growth responses) are not well known for black spruce in Minnesota. The default parameters may be too sensitive or not sensitive enough for black spruce causing the model to show extraneous releases.

The Radial Growth Averaging method is based on the running mean (the comparison of the mean growth rate of adjacent groups of tree-rings). The average radial growth over the preceding 10 year period, M1, and the average radial growth over the subsequent 10-year period, M2 are computed and the percentage growth change (5GC) is obtained by %GC=[(M2-M1)/M1]*100 (Lorimer 1980, 1985; Lorimer and Frelich 1989). The minimum thresholds for releases are 25% growth change for moderate and 50% for major releases. Radial-growth averaging may cause the detection of false releases and the exclusion of true ones. This can be caused by different growth rates in young, small and suppressed trees when compared to older, larger and dominant ones. This could be another issue for this data set. The trees that existed before the first treatments were decades older then the trees that established after. Those older trees have a different growth rate than the younger trees. There are certainly two different age classes in this data set.

With the Absolute Increase method it is possible to determine the absolute threshold for release detection instead of on relative growth. This method was developed by Fraver and White, 2005. They observed that the empirically determined absolute-increase thresholds for each species corresponds to roughly 1.25 times the standard deviation (Trotsiuk et al. 2018) This method only has one threshold. With this method it can be important to know the species autecology (mean growth rate, species sensitivity, and growth responses). This is unknown for black spruce in Minnesota.

The Absolute Increase method detected fewer releases than the radial growth method and these releases that were detected seem to match better with the treatment dates recorded (Table 2.1). In the shelterwood system the absolute increase method detected releases in the 1950's and 1960's (Figure 2.5). The treatments occurred in 1951 and 1961. It could make sense especially with such a small dataset that what are showing up as individual releases could actually be a delay in growth response. This pattern also occured in the clear-cut systems (Figures 2.10 and 2.12).

New information from this research indicates that lowland black spruce in Minnesota does release using alternative silvicultural methods. These methods can be used successfully to create a certain desired future stand where it is economically or ecologically feasible. Further research is needed to determine if the extraneous releases detected are due to a small data set, differing age classes or climatology influences.

Chapter 3: Impacts of Dwarf Mistletoe on Stand Dynamics in Northern Minnesota

Introduction

Black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.) is distributed extensively throughout the boreal forests of North America and is an important species both economically and ecologically (Viereck and Johnston 1990). In both the Lake States region (Minnesota, Wisconsin, and Michigan) and Canada, black spruce is the most important pulpwood species (Viereck and Johnston 1990). In Minnesota, black spruce comprises 648,000 hectares of the 7.04 million forested hectares (Miles 2017) and is second only to aspen (*Populus tremuloides* Michx. and *Populus grandidentata* Michx.) as the most harvested pulpwood species by volume (Minnesota Department of Natural Resources 2017). The black spruce forest constitutes important habitat for many species, including snowshoe hare (*Lepus americanus* Erxleben, 1777), spruce grouse (*Falcipennis canadensis* (Linnaeus, 1758)), American marten (*Martes americana* (Turton, 1806)), salamanders (Salamandridae family), cavity-nesting birds, and other small mammals (Cimon-Morin et al. 2010).

The successional dynamics of black spruce forests in Minnesota are characterized by infrequent stand replacing disturbances (fire return interval of 100 to 700 years) and more small scale gap dynamics (Aaeseng et al. 2003). Infrequent, high intensity stand-replacing fires typically result in even-aged black spruce stands. Black spruce has semi-serotinous cones, which allow copious amounts of seed to disperse after fire. However, seed dispersal is fairly routine in stands over 40 years old, as new seed is produced in most years with heavier seed crops every two to six years (Johnston 1977). As stands age, gaps form due to small scale disturbances such as wind, disease, and mortality due to suppression or age (Johnston and Smith 1983). The creation of gaps can allow for the development of multiple age classes, creating uneven-aged conditions (Viereck and Johnston 1990). A nearly pure black spruce stand can transition to a mix of tamarack (*Larix laricina* (Du Roi) K. Koch), northern white-cedar (*Thuja occidentalis L.*), balsam fir (*Abies balsamea L.* Mill.), white spruce (*Picea glauca* (Moench) Voss), and paper birch (*Betula papyrifera* Marshall) (Viereck and Johnston 1990).

Of the few small scale disturbances that can occur in a black spruce forest in Minnesota is eastern dwarf mistletoe (*Arceuthobium pusillum* Peck; EDM). EDM is a native, parasitic plant that attacks black spruce forming witches brooms, reducing growth and eventually killing trees thus creating mortality circles. It is estimated that 11% to 50% of black spruce stands in Minnesota are infected with EDM (Baker et al. 2012). EDM can begin producing seed within five years and distributes these seeds to new hosts (black spruce) by catapulting the seeds; projected seeds can reach speeds up to 25.5m/sec (Hinds and Hawksworth 1965). The seed is covered in a sticky substance that allows the seed to attach to branches and after a cold period the seed germinates to infect the tree. The seed is also able to stick to passing birds which then carry the seed long distances where it is then cleaned off and deposited onto a branch beginning a new infection center (Hudler et al. 1974; Ostry and Nichols 1979). EDM can kill 75% of infected black spruce within 17 years and spread at a rate of 0.7m/year between among trees (Baker and French 1981; Baker et al. 1982). Stands infested with EDM have reduced regeneration success, reduced growth and yield, and increased risk of transitioning to non-forest brush lands or grasslands (Baker and Knowles 2004). It is hypothesized that historically stand replacing fires played an important role in controlling EDM (Alexander and Hawksworth 1976). Currently, however, there is very limited use of prescribed fire in black spruce management, mainly due to logistical constraints (burning windows, access to sites), financial constraints, and harvest systems that produce insufficient aerial slash. The clear-cut system is hypothesized to be an effective strategy in controlling EDM in black spruce stands when all standing live black spruce greater than five-feet in height are removed. However, while a clear-cut does remove aboveground biomass, it will never be able to replicate a stand replacing fire. It is currently the policy on state administered lands in Minnesota that all trees over five-feet are removed (MNDNR 2018). However, trees shorter than five feet can allow mistletoe to establish in a regenerating stand (French et al 1968, Baker and Knowles, 1995).

As a major component of the boreal forest, the black spruce cover type is quite common, however, there are still many unanswered questions regarding the stand dynamics of these slow-growing systems. Long-term studies with consistent remeasurements are rare in black spruce (but see Anderson et al. 2018). However, there have been increasing numbers of studies in Canada regarding black spruce forests in the last few decades (e.g., Groot 1995, 2014; MacDonell and Groot 1997; Cimon-Morin et al. 2010; Soucy et al. 2012; Lafleur et al. 2016). This has led to an increase in the knowledge of the black spruce stand dynamics, however, Canadian black spruce may have different soils, climates, and other physiographic conditions than in the Lake States; the impact that these difference may have on black spruce stand dynamics are unknown (Viereck and Johnston 1990).

The goal of this research is to examine how varying levels of dwarf mistletoe infection impact overstory and understory structure and composition of black spruce in northern Minnesota. There has been research, especially in Canada, regarding the stand dynamics and growth and yield of black spruce. There has also been considerable research on the biology and life cycles of EDM in Minnesota. However, there is limited research on the interaction between EDM and stand dynamics in black spruce. EDM has the potential to influence overstory and understory structure and composition potentially resulting in stands with different successional trajectories and influence both the economic and ecological benefits gained from the stands. Results from this research will fill a gap in knowledge on how EDM influences stand developmental processes in lowland black spruce.

Methods

Study Area

Black spruce is a common tree across the northern forests in North America extending from Labrador and Maine in the east to the west in Alaska and British Columbia. Its northern range extends to the northern tree line of the boreal forest and south to Minnesota, Wisconsin, and Massachusetts. The southern extent of the boreal forest in northern Minnesota resides within the Laurentian Mixed Forest Provence (LMFP) (MNDNR 2019). The LMFP consists of a diverse mix of conifer forests, mixed hardwood and conifer forests, and conifer bogs and swamps. The conifer bogs and swamps can be described as lowland conifers or peatlands and are characterized by deep, acidic, nutrient poor, poorly drained soils dominated by tree species such as black spruce and eastern larch (MNDNR 2019). Black spruce site index in peatlands is fairly low with some stands having site index values below 4.6 meters at 50 years; more productive sites can reach up to 13.7 meters in 50 years (Johnson 1977).

Annual precipitation of the region range between 135 cm and 174 cm falling as rain or snow water equivalent) with the majority of the precipitation falling during the growing season. Winters are typically frigid cold with mild to warm summers. Normal annual temperatures range from 1^{o}C to 4^{o}C. (MNDNR 2019). Due to poor access and low productivity of the lowland conifer forests, there has been relatively little conversion of sites for agriculture or urbanization. However, in some areas of northern Minnesota there were attempts to increase productivity by draining through ditches; this was overall not very successful.

Sampling Design

Using the MN DNR Forest Stand Inventory Database a query was done to select black spruce stands greater than five hectares in size, within 600m from a navigable road, classified as a lowland conifer stands in a non-stagnant conditions (site $index_{50}$ > 7 m) between the ages of 60-100 years. Site selection was completed using ArcMap (ESRI) with shape files from the Minnesota Department of Natural Resources Forest Stand Inventory (MNDNR-Division of Forestry) accessed through the Minnesota Geospatial Commons. Stands were further divided based on the damage code for EDM and then further by the damage severity code. There were three categories: dwarf mistletoe free, low severity, and high severity. Low severity stands were defined as EDM ratings less than 50% severity and high severity stands had EDM ratings greater than 50%. However, during stand inspections the damage severity codes did not accurately match infestation levels on the ground, especially for what were originally coded as EDM free stands. Additional landowners were contacted to assist with site selection for EDM free stands. These stands were also located in close proximity to Lake County, Minnesota and are in the Laurentian Mixed Forest Provence, care was taken to ensure that these sites were greater than five hectares, 600m from navigable road, lowland non-stagnant site, and 60-100 years of age. This resulted in ten stands sampled during the summer of 2017 (Figure 3.1, Table 3.1).

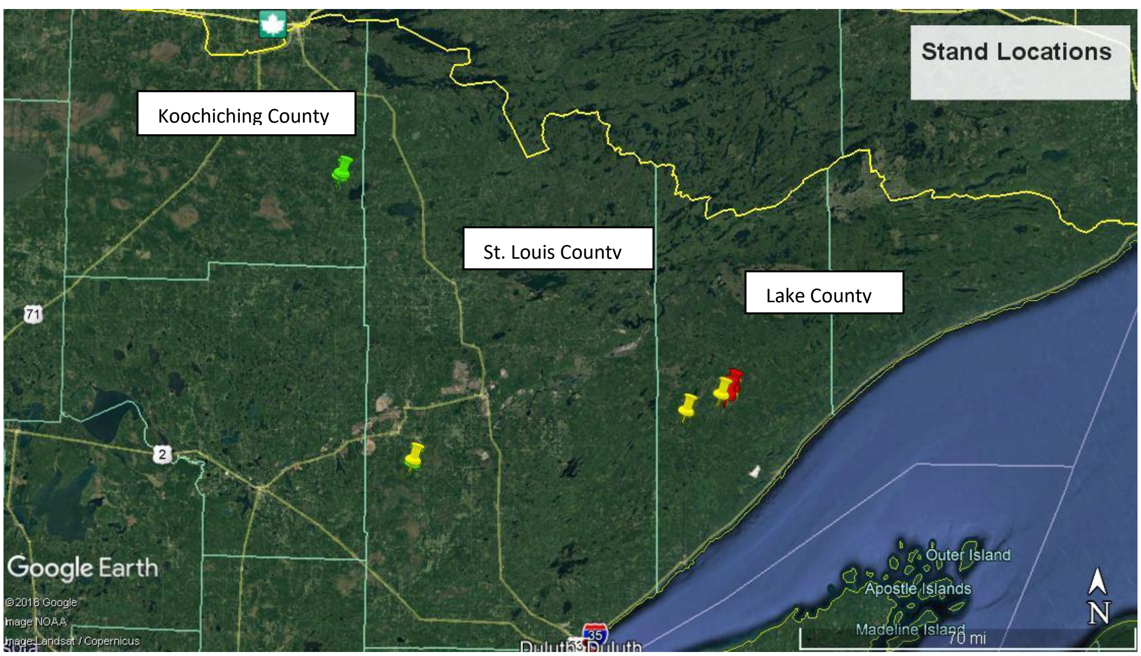


Figure 3.1: Stands were located in three counties in North East Minnesota, Koochiching County, St. Louis County, and Lake County. Green pins indicate no mistletoe stands, yellow indicate low mistletoe stands, red indicate high mistletoe stands.

Table 3.1: Stand descriptions and locations of study sites. Of the ten stands sampled three were mistletoe free, four were low mistletoe, and three were high. Six of the ten units were initially thought to be free of mistletoe but due to the amount of mistletoe found three were changed to a low mistletoe category after sampling.

Stand Name	Mistletoe Category Before Sampling	Mistletoe Category After Sampling	County	Landowner	Stand Age	Site Index (m)	Location
B1	No Mistletoe	No Mistletoe	St. Louis	Blandin	85	11.9	47°16'41.78"N92°52'39.48"W
M1	No Mistletoe	No Mistletoe	Koochiching	Molpus	60-100[1]	12.2[2]	48° 7'29.84"N 93°13'3.63"W
M2	No Mistletoe	No Mistletoe	Koochiching	Molpus	60-100[1]	12.2[2]	48° 8'1.40"N 93°12'28.86"W
S1	No Mistletoe	Low Mistletoe	Lake	MNDNR	74	9.4	47°26'13.20"N91°4

							0'56.74" W
S2	No Mistletoe	Low Mistletoe	Lake	MNDNR	75	8.8	47°29'9.40"N 91°31'44.05"W
B2	No Mistletoe	Low Mistletoe	St. Louis	Blandin	97	11.9	47°17'17.50"N92°52'28.58" W
S7	Low Mistletoe	Low Mistletoe	Lake	MNDNR	76	13.4	47°29'18.01"N91°29'27.05" W
S21	High Mistletoe	High Mistletoe	Lake	MNDNR	92	11.6	47°29'2.37"N 91°29'56.02"W
S22	High Mistletoe	High Mistletoe	Lake	MNDNR	92	11.9	47°29'20.30"N91°30'0.58"W
S23	High Mistletoe	High Mistletoe	Lake	MNDNR	90	11.9	47°30'29.03"N91°29'1.23"W

[1]There was no age reported from the landowner regarding age of stand. We asked for units between 60 and 100 years of age.

[2]There was not a site index reported from the landowner however there are multiple state owned stands with an average site index of 12.2m within 3km.

Due to differences between the MN DNR Forest Stand Inventory Database and sampled stand conditions, the EDM severity classification was updated based on sampled data (Table 3.1). Stands where over 50% of the plots contained live EDM infected trees or dead trees with evidence of EDM infection such as epicormic branching (witches' brooms) or branch swelling were categorized as high EDM infection. Those stands with less than 50% of the plots containing live EDM infected trees or dead trees with evidence of EDM infection were categorized as low EDM infection. Stands without plots containing evidence of past or current EDM infection were categorized as no dwarf mistletoe infection. One stand located in Koochiching County did have a small area infected with EDM that was found while walking through the unit. The infection site was located further than 40m (two chains) away from any plots which is both the Minnesota DNR and Forest Service recommendation while performing a salvage cut to ensure that there is no infection (MNDNR 2018).

To fully cover the stand and capture the spatial variability of dwarf mistletoe infections, a sampling design using six fixed radius plots in an unit (henceforth referred to as the unit) and transects were used (Figure 3.2). The first sampling unit was predetermined for each site on ArcGIS. On the ground after arriving at the predetermined starting point a random azimuth was selected using either a compass or a sheet of randomly generated azimuths to offset the first plot 10m in the random direction to reduce bias. The unit consists of six $1/100^{th}$ hectare plots spaced 30 m x 60 m. The unit generally was a 2 x 3 rectangular design; however, irregular shaped stands did result in a not rectangular design. However, the number of plots (6) and the spacing (30 m x 60 m) remained consistent. Transects between units were 100 m in length.

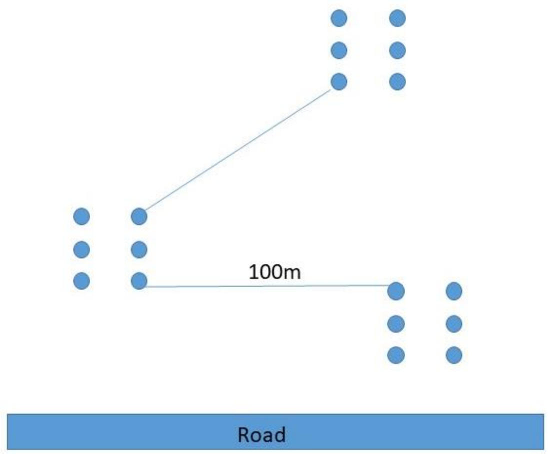


Figure 3.2: In each stand there were three units comprised of six plots. These units were located 100m apart.

Within each of the fixed radius plots, all overstory trees (diameter at breast height (dbh) > 3 cm) were measured; variables collected on overstory trees included species, dbh, status (live/dead), dwarf mistletoe rating if applicable (Figure 3.3), mortality class if applicable (Table 3.2), and possible cause of death if apparent and applicable. Every 4th tree height and height to first broom (measured at the middle of the broom) was taken if applicable. Three smaller fixed radius subplots (1/1000th ha) were established to quantify sapling/seedlings. The subplots were spaced 2 m from the center of the main plots at 0º, 120º, and 240º of the subplot center. Within each subplot saplings were defined as all trees less than 3cm and over 1.3m in height; measures for saplings included height, dbh, live/dead status, species, and dwarf mistletoe presence. Seedlings were defined as tree species less than 1.3m in height and were tallied by species live/dead and dwarf mistletoe presence. Between each unit a 100m transect 3m wide was taken resulting in a total area of 300m^2 or 600 m^2 for the two transects. The transect began at the last plot center of the first unit and end at the first plot center of the second unit. Along each transect any tree with dwarf mistletoe was recorded with the distance along the transect. Dwarf mistletoe rating (DMR) is recorded for each tree infected with dwarf mistletoe along the transect.

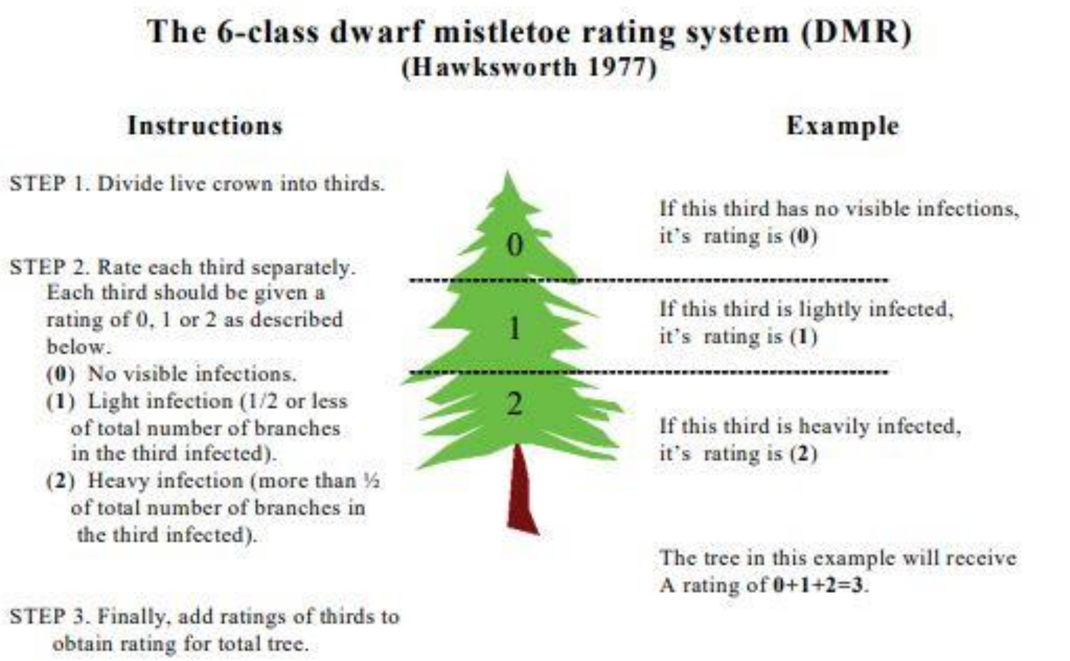


Figure 3.3: Dwarf Mistletoe Rating System (Hoffman 2004)

Table 3.2: Mortality classes used to quantify the level of mortality in the field. This was used on all dead overstory trees.

Mortality Classes	
1	Tree with needles still attached
2	Tree with main branches and small branches and perhaps some twigs remaining
3	Tree with main branches still remaining
4	Tree with many main branches missing
5	Snag – Only main stem remaining

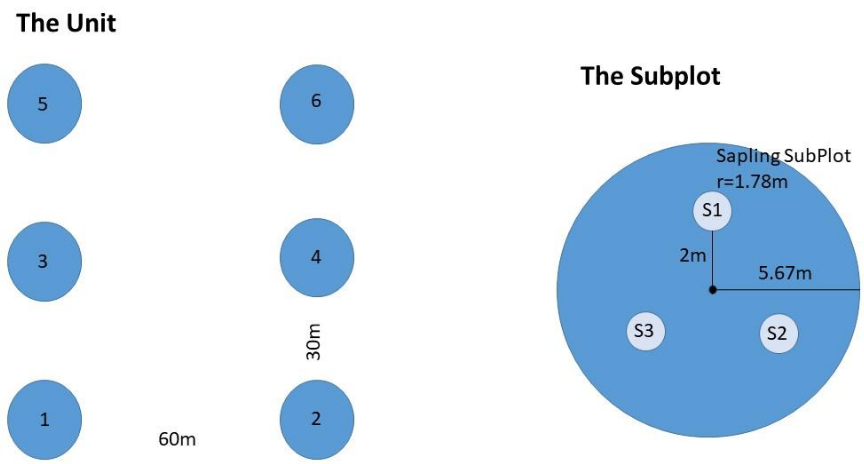


Figure 3.4: Within the unit the subplots were arranged in a 3x2 square 60m x 60m. The subplot was 1/100th of a hectare with a radius of 5.67m. There were three sapling subplots located at 0^o, 120^o, and 240^o 2m from the center of the plot with a size of 1/1000th of a hectare with a radius of 1.87m.

Statistical Analysis

At each plot, trees per hectare, basal area, diameter at breast height, Shannon's diversity index (Hill 1973), Shannon's evenness (Hill 1973), and richness were calculated. The data was summarized at the plot level, the unit level, the stand level, and by the dwarf mistletoe class. Analysis of variance (ANOVA) in R (R Core Team 2015) was used to test for differences among the dwarf mistletoe categories at the plot level. When significant differences were observed, Tukey's honestly significant difference test in R (R Core Team 2015) was used. A significant value of $p > 0.1$ was used due to the high variability of the natural system. Diameter distributions of DBH for each species for each level of infection were constructed using 5cm diameter classes. The species of note were live and dead black spruce and tamarack. There were multiple other species recorded, however their numbers individually were small and were grouped into another category.

Results

Overstory Stand Characteristics

Overall density among the three mistletoe classes was variable; total basal area per hectare (BA) ranged between $24.64 m^2 ha^{-1}$ and $35.94\ m^2 ha^{-1}$ (Table 3.3). BA was significantly different between the no mistletoe and low mistletoe class (Table 3.3 & 3.4). There was less variability in total trees per hectare (TPH) which ranged between 2741 and 2215 and there was no significant difference among the mistletoe classes (Table 3.4). There was a significant difference in live black spruce BA and TPH among the mistletoe classes (Table 3.4); the no mistletoe class had significantly greater BA and TPH compared to the low and high classes (Table 3.3). The reverse was true for live tamarack. As black spruce decreased tamarack increased (Figure 3.5).There were also significant differences in the density of standing dead trees; the high mistletoe stands had significantly greater dead BA compared to the no and low stands. However, this relationship did not hold up for the number of trees (Table 3.4). There were few differences in average diameter at breast height (DBH) among mistletoe classes (Table 3.4). Live tamarack trees were significantly larger in the high mistletoe stands compared to the no and low mistletoe stands (Table 3.3).

Table 3.3: Summary statistics by mistletoe class for stands in northern Minnesota. Associated standard errors are in parenthesis. Letters represent significant differences among the three mistletoe classes

	Basal Area (m^2/Ha)		
	No Mistletoe	Low Mistletoe	High Mistletoe
Black Spruce Live	32.50 (2.66)a	17.51 (1.92)b	17.79 (4.27)b
Black Spruce Dead	2.38 (0.68)b	1.81 (0.33)b	4.69 (0.75)a
Tamarack Live	1.05 (0.42)b	2.67 (0.72)b	7.48 (1.59)a
Tamarack Dead	0.01 (0.01)b	0.04 (0.02)ab	0.18 (0.09)a
Total Live	33.56 (2.76)a	22.65 (1.39)b	26.29 (3.19)ab

Total Dead	2.38 (0.68)b	1.99 (0.36)b	4.88 (0.76)a
Total	35.94 (2.67)a	24.64 (1.32)b	31.16 (3.57)ab
	Trees Per Hectare		
	No Mistletoe	Low Mistletoe	High Mistletoe
Black Spruce Live	2341.81 (194.59)a	1337.88 (241.43)b	1003.70 (247.11)b
Black Spruce Dead	355.56 (118.08)ab	186.36 (31.93)b	481.48 (106.66)a
Tamarack Live	59.26 (19.47)b	186.36 (45.49)b	379.63 (103.70)a
Tamarack Dead	5.56 (3.93)a	9.09 (3.46)a	18.52 (7.05)a
Total Live	2379.63 (198.56)a	1951.52 (180.42)a	1812.96(196.96)a
Total Dead	361.11 (117.49)ab	213.64 (31.04)b	501.85 (103.95)a
Total	2740.74 (225.93)a	2215.15 (183.90)a	2314.81 (287.23)a
	Diameter at Breast Height (cm2)		
	No Mistletoe	Low Mistletoe	High Mistletoe
Black Spruce Live	13.10 (0.94)a	12.05 (0.57)a	13.46 (0.93)a
Black Spruce Dead	7.25 (0.74)a	7.48 (1.05)a	9.00 (0.88)a
Tamarack Live	3.80 (0.89)b	6.55 (1.39)b	11.77 (1.14)a
Tamarack Dead	0.22 (0.16)b	0.54 (0.19)ab	1.18 (0.46)a
Total Live	13.12 (0.93)a	11.44 (0.29)a	12.19 (0.58)a
Total Dead	7.13 (0.74)a	7.86 (1.03)a	9.39 (0.90)a

Total	12.44 (0.86)a	10.99 (0.25)a	11.70 (0.45)a

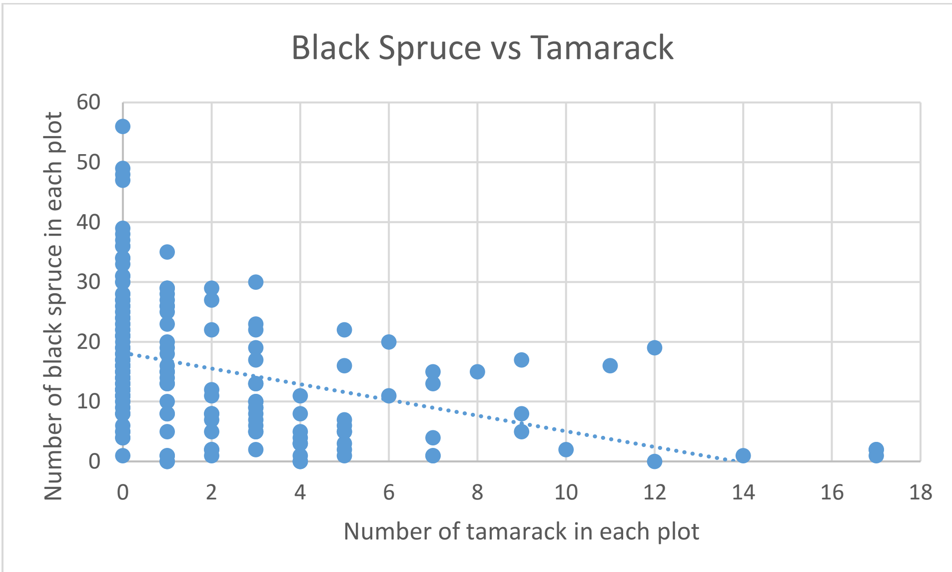


Figure 3.5: Scatter plot with the number of black spruce trees on the y axis and tamarack on the y axis. As the number of black spruce in each plot decreased the number of tamarack increased. Correlation = - 0.4.

Table 3.4: Results of individual ANOVA tests for differences between mistletoe classes. Bolded Values are significant at p=0.1.

	BA		TPH		DBH	
	F	p	F	p	F	p
Black Spruce Live	7.99	**0.002**	8.44	**0.001**	0.74	0.49
Black Spruce Dead	7.39	**0.002**	3.21	**0.06**	1.12	0.35

Tamarack Live	10.55	**0.0004**	6.13	**0.006**	11.02	**0.0003**
Tamarack Dead	3.12	**0.06**	2.41	0.11	2.41	0.11
Total Live	4.32	**0.02**	2.33	0.12	1.63	0.21
Total Dead	7.32	**0.003**	3.06	**0.06**	1.51	0.24
Total	3.76	**0.04**	1.154	0.23	1.49	0.24

Diameter Distributions

All mistletoe classes displayed the same unimodal diameter distribution with slight leftward skews (Figures 3.6 – 3.8). The low and high mistletoe classes have slightly wider diameter distributions with trees in the 30 cm + classes. The largest tree in the no mistletoe class was a black spruce with a DBH of 29.8cm, in the low mistletoe class a northern white cedar with a DBH of 36.2 cm and in the high was a tamarack with a DBH of 41.3 cm. There was an increase in the number of species in the smaller diameter classes In both in the low and the high mistletoe classes (see appendix A for other species) .

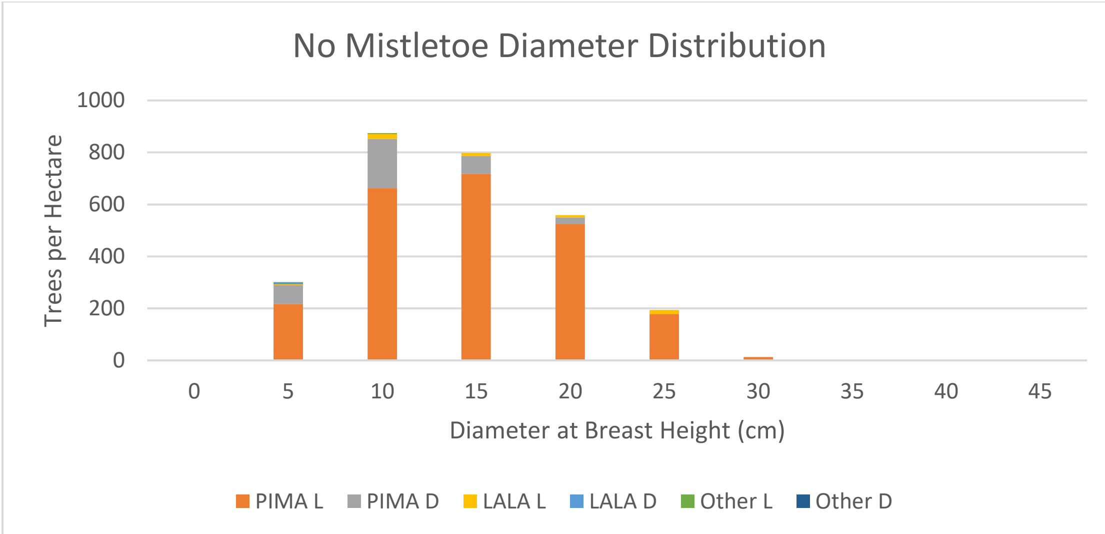


Figure 3.6: Diameter distribution of overstory trees in the no mistletoe class (see Appendix A for other species.)

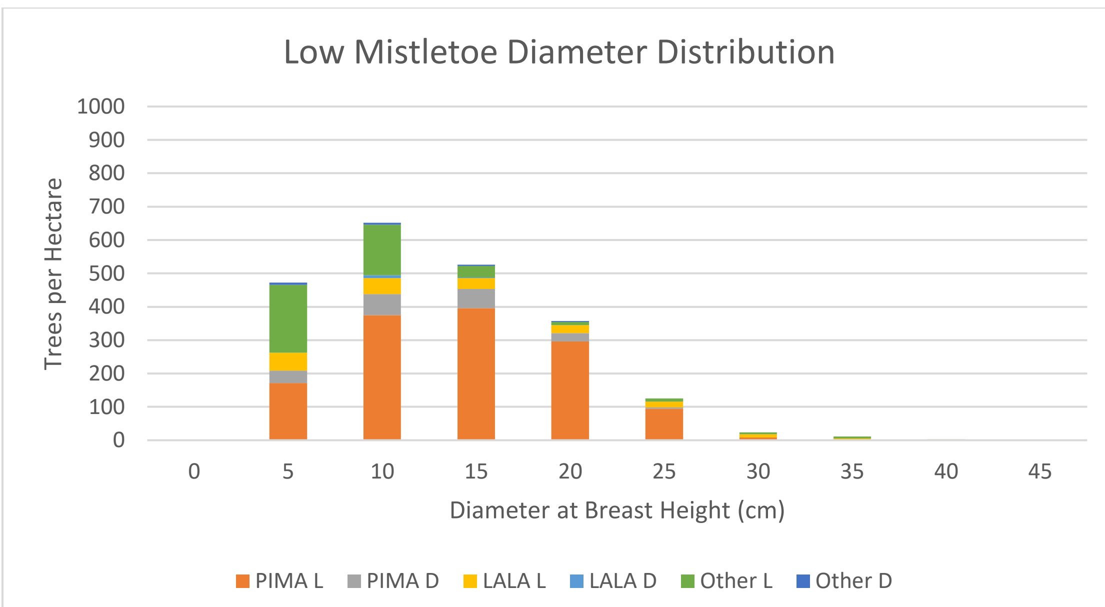


Figure 3.7: Diameter distribution of overstory trees in the low mistletoe class (see Appendix A for other species.)

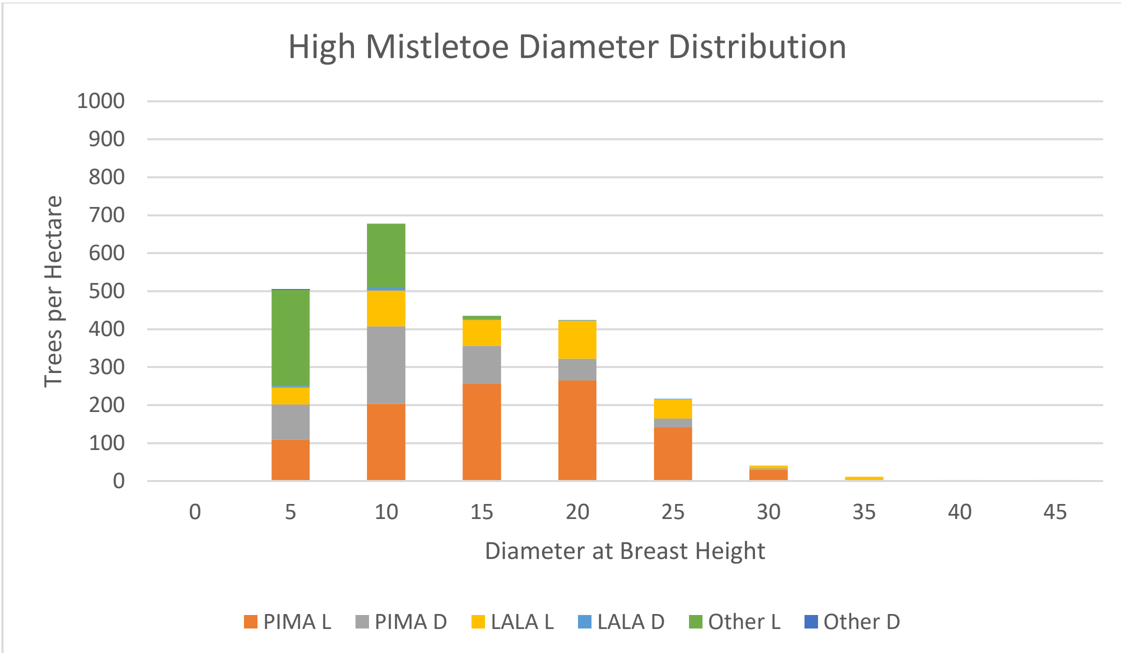


Figure 3.8: Diameter distribution of overstory trees in the high mistletoe class (see Appendix A for other species.)

Dwarf Mistletoe Rating

DMR was significantly greater in the high mistletoe class for both black spruce, tamarack, and total DMR compared to the no and low mistletoe classes (Table 3.5 & 3.6). There was no significant difference between the no mistletoe and low mistletoe stands for DMR levels (Table 3.5). Total DMR was over three times greater in the high mistletoe compared to the low mistletoe classes. Additionally, while EDM is rare on tamarack, there was significantly greater amounts observed in the high mistletoe stands than the low and no mistletoe stands. The highest rating for DMR on tamarack was 3.

Table 3.5: DMR rating on live black spruce and tamarack. DMR was not measured on dead trees. Letters represent significant differences among the three mistletoe classes

	Dwarf Mistletoe Rating		
	No Mistletoe	Low Mistletoe	High Mistletoe
Live Black Spruce	0 b	6.30 (1.94)b	19.56 (5.79)a
Live Tamarack	0 b	0.03 (0.02)b	0.24 (0.10)a
Total	0 b	6.33 (1.94)b	19.80 (5.76)a

Table 3.6: Results of individual ANOVA tests for differences between mistletoe classes. Bolded Values are significant at p=0.1.

	f	p
Black Spruce Live	8.62	**0.001**
Tamarack Live	5.24	**0.01**
Total	8.92	**0.001**

Seedlings

Across all three mistletoe categories there was strong regeneration; all categories averaged over 2,500 stems per the acres of live regeneration (Table 3.7). There was no significant difference among the mistletoe classes for total live seedling TPH, total dead seedling TPH, and total TPH (Table 3.8). However, there were significantly more live black spruce seedlings in the no mistletoe stands compared to the low and high mistletoe stands (Table 3.7). Balsam fir seedling density was greater in the low mistletoe stands compared to the no mistletoe stands. (Table 3.7) Dead black spruce seedlings did not vary among the three classes (Table 3.8).

There are on average approximately 80 live black spruce seedlings per ha in both the low and high mistletoe stands that are infected to EDM (Table 3.9); these levels were significantly greater than the no mistletoe stands (Table 3.9 & Table 3.10). Overall, these seedlings represent a small portion (~5%) of the total live black spruce advanced regeneration.

Table 3.7: Seedlings not infected with mistletoe per hectare by mistletoe class. Northern white-cedar (*Thuja occidentalis*) was the only seedling found not included in the table. Letters represent significant differences among the three mistletoe classes

Seedlings Without Mistletoe			
	No Mistletoe	Low Mistletoe	High mistletoe
Black Spruce Live	3759.26 (944.44)a	1752.53 (315.37)b	1679.01(311.64)b
Tamarack Live	43.21 (28.95)a	252.53 (98.63)a	382.72 (192.10)a
Balsam Fir Live	18.52 (13.09)b	1398.99 (592.5)a	580.25 (250.87)ab
Black Spruce Dead	216.05 (90.93)a	50.51 (27.48)a	74.07 (43.43)a

Total Live	3820.99 (966.95)a	3459.6 (511.65)a	2641.98 (319.56)a
Total Dead	240.74 (106.38)a	55.56 (29.01)a	141.98 (49.96)a
Total Seedlings	4061.73 (939.23)a	3601.01 (505.57)a	2870.37 (294.56)a

Table 3.8: Results of individual ANOVA tests for differences between mistletoe classes. Bolded Values are significant at p=0.1.

	F	p
Black Spruce Live	4.47	**0.02**
Tamarack Live	1.91	0.17
Balsam Fir Live	3.21	**0.06**
Black Spruce Dead	2.49	**0.10**
Total Live	0.84	0.44
Total Dead	2.19	0.13
Total	0.88	0.43

Table 3.9: Seedlings infected with mistletoe per hectare by mistletoe class. Only black spruce seedlings were infected. See appendix b for other species. Letters represent significant differences among the three mistletoe classes

Seedlings Infected With Mistletoe			
	No Mistletoe	Low Mistletoe	High mistletoe
Black Spruce Live	0 b	85.86 (31.22)a	86.42 (47.31)a
Black Spruce Dead	0 b	5.05 (5.05)b	67.90 (27.43)a

Table 3.10: Results of individual ANOVA tests for differences between mistletoe classes. Bolded Values are significant at p=0.1.

	F	p
Black Spruce Live	2.09	0.14
Black Spruce Dead	6.38	**0.005**

Diversity

There were no significant differences between the high and low mistletoe categories in the overstory when looking at all three measures of diversity. There was however significant differences between the two mistletoe categories and the no mistletoe category with the no mistletoe category being the least diverse (Table 3.11). Seedlings were the most diverse category in the low mistletoe category. There is no significant difference between the no mistletoe and the high mistletoe category in regards to diversity measures with seedlings.

Table 3.11: Diversity measures by mistletoe class in both the overstory and seedlings. Letters represent significant differences among the three mistletoe classes.

		Shannons Diversity Index	Richness	Shannons Evenness
Overstory	No mistletoe	0.12 (0.03)b	2.11 (0.14)b	0.15 (0.10)b
	Low mistletoe	0.82 (0.20)a	4.17 (0.53)a	0.56 (0.24)a
	High mistletoe	0.90 (0.04)a	4.00 (0.08)a	0.66 (0.07)a
Seedlings	No mistletoe	0.05 (0.03)b	0.47 (0.10) b	0.54 (0.09)b
	Low mistletoe	1.44 (0.24)a	2.42 (0.23)a	2.56 (0.18)a
	High mistletoe	0.06 (0.03)b	0.47 (0.08)b	0.59 (0.08)b

Table 3.12: Results of individual ANOVA tests for differences between mistletoe classes. Bolded Values are significant at p=0.1.

	Shannon's Diversity		Richness		Shannon's Evenness	
	F	p	F	p	F	p
Overstory	13.29	**0.000001**	7.56	**0.003**	14.76	**0.000001**
Seedlings	9.6	**0.0007**	6.88	**0.004**	12.84	**0.0001**

Discussion:

The presence and amount of EDM influences stand structure and composition and can thus result in changes in the forest community (Table 3.3, Figures 3.5 – 3.7). Stands infected with mistletoe had variability in terms of stand structure. For example, the standard errors for black spruce TPH for the low and high mistletoe categories, 241.43 and 247.11, respectively, were greater than the standard error of the no mistletoe category, 194.59. The higher variability in stand structure when dwarf mistletoe is present is due the spatially explicit nature of the disease. This is different than density dependent mortality. For example, there was no significant difference in the density (TPH) of dead black spruce in the no mistletoe stands and the high mistletoe stands (Table 3.3). In the high mistletoe class the cause of mortality is predominantly from EDM where as in the no mistletoe class the cause of mortality is due to suppression.

EDM also shifts stand composition since it creates small and slowly expanding gaps (Baker and French 1991). In mistletoe free stands, black spruce represented 98% of the total trees per hectare compared to 69% in the low mistletoe and 53% in the high mistletoe stands. On average there was twice as many overstory species in stands with mistletoe compared to stands with no mistletoe (Table 3.11). Additionally, the diameter distributions of the low and high mistletoe stands had a greater number of species and amount of species other than black spruce in the lower and higher diameter classes (Figure 3.5 – 3.7). The shift in species composition after small-scale disturbances are common since the disturbance creates gaps and changes the environmental conditions often allowing for the development of multiple age classes (Nyland 2016). The development of multiple age classes and species composition shifts in black spruce stands have been previously documented (Viereck and Johnston 1990).

While overstory measurements in EDM stands may appear to be more structurally and compositional diverse, it is important to consider the future impact of EDM. While the current sampling design represents one point in time, by assessing both the current levels of EDM through DMR ratings and by quantifying mistletoe presence on seedlings, predictions can be made about future impacts since EDM will kill 75% of infected trees within 17 years (Baker and French 1981; Baker et al 1982). In the high mistletoe stands, and to a lesser extent in the low mistletoe stands, many of measures of stand structure and composition (black spruce TPH, BA/ha, dead BA/ha, etc.) will change within the next two decades without management. This has implications not only for the current overstory but also the mid-story and seedling layer. In the 5cm diameter class within high mistletoe stands, roughly only 100 of the 400 trees are black spruce (Figure 3.7). The loss of the overstory and the change in composition in the mid-story will transition these stands from black spruce dominated to mixed lowland conifer and hardwood stands.

EDM is also influencing seedling regeneration in terms of density, diversity, and health. While there was no significant difference among the classes for total live, total dead, or total seedling densities, there were significant differences in the amount of black spruce and balsam fir regeneration among EDM classes. Black spruce regeneration was significant greater in the no mistletoe stands compared to the low and high mistletoe stands. While, the no mistletoe stands had lower balsam fir regeneration than the low mistletoe stands. Additionally, a subset of the regeneration in the low and high mistletoe stands were impacted by EDM and while currently alive will not likely reach the overstory (Baker and Knowles 2004). The type, health, and quantity of regeneration have implications for the future forest.

Stands infected with dwarf mistletoe are on a fast track transitioning to a mixed species stand. This has implications both economically and ecologically. Hanks et al. (2011) found that 56% of stands were infected. Stands infected with mistletoe have a significantly lower basal area (54% lower (table 3.3)) and TPH (49% lower (Table 3.3)). This has significant implications to the state of Minnesota where nearly 10% of the state's forest land is black spruce (Miles 2017) and black spruce is the second most harvested pulp species.

Appendix A

Table A: Other species (not including black spruce or tamarack which was found in all categories) found in each mistletoe category, no mistletoe (Figure 3.6), low mistletoe (Figure 3.7), high mistletoe (Figure 3.8). [1]Only black spruce and tamarack were found to be dead in the no mistletoe category.

	Other Live	Other Dead
No Mistletoe	*Abes balsamea* (balsam fir) *Betula papyrifera* (paper birch)	[1]
Low Mistletoe	*Abes balsamea* (balsam fir) *Betula papyrifera* (paper birch) *Populus Tremuloides* (quaking aspen) *Alnus incana* (speckled alder) *Fraxinus nigra* (black ash) *Thuja occidentalis* (northern white-cedar)	*Abes balsamea* (balsam fir) *Betula papyrifera* (paper birch) *Populus Tremuloides* (quaking aspen) *Alnus incana* (speckled alder)
High Mistletoe	*Abes balsamea* (balsam fir) *Betula papyrifera* (paper birch) *Alnus incana* (speckled alder) Prunus serotine (black cherry)	*Abes balsamea* (balsam fir)

Chapter 4 Conclusion:

The increment cores collected from the Compartment Study on the Big Falls Experimental Forest provides year by year growth information from a long term silvicultural study of black spruce. These types of studies are nearly nonexistent in the Lake States. This study is nearly 70 years old, a possible rotation age for black spruce in the region.

This initial research, and the research that will stem from it provides support for alternative silviculture methods to be used for black spruce. In all treatment studies, the black spruce responded and produced a large release. Even trees that were over 100 years during the first treatment showed evidence of release. This sort of response has been well studied in other species but not in black spruce.

Eastern Dwarf Mistletoe is a major problem for stands in the Lake States Region and throughout the parasite's range. Over 56% of stands in Minnesota are expected to be infected with EDM, based on previous studies done by Hanks et al. in 2011, and once infected the tree is likely to die in 17 years or less. EDM transforms stands that were once even aged nearly pure black spruce to uneven aged and mixed species.

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