A REVIEW OF SILVICS, STAND DYNAMICS, DENSITY MANAGEMENT, AND VEGETATION MANAGEMENT IN THE ONTARIO BOREAL FOREST

by

Ethan Brandt
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An Undergraduate Thesis Submitted in
Partial Fulfillment of the Requirements for the
Degree of Honours Bachelor of Science in Forestry

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ABSTRACT

Brandt, E.B. 2023. A Review of Silvics, Stand Dynamics, Density Management, and Vegetation Management in the Ontario Boreal Forest. 74 pp.

Keywords: adaptive management, brushing, commercial thinning, density management, herbicide, initial spacing, pre-commercial thinning, renewal, silviculture, vegetation management

Adaptive forest management requires constant re-evaluation of the efficacy and impact of current practices. Continuous development of information is key to any adaptive management regime, especially in the face of large-scale changes to the environment, economy, society, and the forest itself. This is why it is important to always look to the future for alternatives to what may be working now. Two common management objectives in the establishment and tending of boreal forest stands are stand density management and vegetation management. These management areas rely heavily on tree silvics and stand dynamics to be properly applied. This review outlines the species silvics and stands dynamics of merchantable boreal tree species in Ontario. It then explores the concepts of both density and vegetation management as they have been established through previous literature. The current methods of density and vegetation management in the Ontario boreal are outlined and to what degree they are used in what situations. Finally, several alternative vegetation management options which reduce the reliance on herbicides are explored.

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INTRODUCTION

A great deal of time and effort has been spent understanding the dynamics of forests so we can better manage the forest ecosystem and better utilize the benefits from the forest, both commercial and non-commercial. We, as forest managers, aim to efficiently use these resources while ensuring the needs of the future are met, and this is often the explanation given when referring to the concept of sustainable forestry. A major component of sustainable forestry is the practice of silviculture. Silviculture is both the theory and the practice of controlling the establishment and growth at the tree and stand levels to meet desired management objectives set by forest managers and landowners (Achim et al. 2022). This includes considering all management factors of the stand, such as species associations, soil types, effective harvest treatment, regeneration treatments, and the establishment and intermediate treatments. Silviculture is often considered both an art and a science (Nyland 2016). It is considered an art because there is a certain degree of personal reflection and introspection based on some previous knowledge of what has worked before, what hasn't worked, and what may work in the future. It is considered a science because, at its very core, silviculture will follow some basic renewal principles solidified through trials, results, and peer-reviewed literature conducted by those bold enough to test new management strategies.

The fickle nature of silviculture and what it means to be a silviculturist are summarized succinctly in the preface to the *Forest Management Guide to Silviculture in the Great Lakes-St. Lawrence and Boreal Forests of Ontario* (MNRF 2015), where it is stated:

> *"The job of the silviculturalist* [sic] *is a mixture of routine application of time tested treatments and experimentation with novel techniques or sites, interspersed with the occasional head scratching when one or the other does not provide the expected outcome. Our knowledge has progressed to a point where successes far outnumber failures, but cause and effect is not always obvious, nature is messy, and things do not always go as planned. This does not mean we throw our hands up in frustration with the occasional failure, but that we embrace the uncertainty with which we are working, and commit to learning through practice. As long as we never answer "why do you do it that way" with "cause that's how we've always done it" we can be assured that ineffective practices will be identified and effective practices will get even better."*

One main concept within the scope of silviculture is *Renewal*. Renewal is defined in the Ontario Ministry of Natural Resources and Forestry 2020 *Forest Management Planning Manual*:

"*The silvicultural operations undertaken to stimulate and promote the establishment and growth of desired future forest stands, which may include the activities of site preparation and regeneration.*"

Renewal is an important portion of silviculture because forest managers must renew forests to previous or near-previous conditions. This obligation remains regardless of the environmental or social conditions surrounding the forest, be it changes in vegetation dynamics in forests, climate change, unforeseen disturbance of the forest, or through a change in public perception of practices. Thus, it is important to ensure that as foresters we are constantly taking appropriate steps to renew the forest.

The dynamic nature of the forest requires dynamic management approaches to be taken. Just as the forest changes, so must how we view management strategies. Forest management practices are essential to maintaining the ecological, social, and economic sustainability of our forests. However, the dynamic and complex nature of forest ecosystems means that effective management practices must constantly evolve and adapt to changes in the environment, economy, and society. As our understanding of the impacts of climate change and other environmental factors on forest ecosystems grows, it is critical that we continually research and learn about new techniques and practices that can help to mitigate these impacts. Additionally, changes in economic and social conditions can impact the demand for forest products and services, as well as the values and priorities of forest stakeholders. By staying informed and adapting our forest management practices to these changes, we can ensure that our forests continue to provide the benefits and services that are valued by society while maintaining their long-term health and productivity.

Fundamentally sound renewal practices made today can have lasting effects in the future. Poor renewal practices can prove to be even more detrimental, and their effects can outlast the foresters who choose to use them. This underlines the importance of continuous learning. One of the more important areas of silviculture is the renewal activities that are implemented to ensure that the stand is established and tended to effectively. It is an area that can be constantly improved on as new research is completed. The management of forest density and vegetation is critical to maintaining the health and productivity of the forest, as well as ensuring its long-term sustainability. Managing stand density is important to ensure that we are getting the optimal efficiency off the landbase. Increasing our yield per tree means that we can get more off the land per smaller unit area. This can allow us to manage some areas more intensively, and in other areas more effectively for other ecological goals across the landscape. Vegetation management is important for maintaining target species composition across the landscape. Maintaining species composition is imperative for timber supply, economic security, and ecological harmony. Ensuring the proper establishment of a stand after harvest is also a requirement of the *Crown Forest Sustainability Act*, 1994 (CFSA). Infiltration of invasive or undesirable species can limit the proper establishment of stands and cause changes to the ecological balance.

This paper aims to provide an overview of the current literature on density and vegetation management, and it will also look forward to the future on how we can improve upon some of the methods we use now. First, the economic importance and silvics of the common boreal tree species will be outlined briefly. Stand dynamics will then be reviewed, which provide the basis for the assemblage of species on sites, their succession, and their common disturbances. Then, the basics of stand density management will be defined, justified, and how stand density management affects trees in the Ontario boreal forest will be demonstrated. The current density management methods in use will be briefly reviewed. Justification for vegetation management in the boreal forest and its effect on forest stands will be reviewed along with current vegetation management methods. Because of its increasing importance with the change of societal views, the future of vegetation management without or with limited herbicide will also be explored. This includes the reduction of methods involving herbicides. In doing so, hopefully, the reader will acquire a better understanding of the importance of effective forest management practices in the Ontario boreal forest, and the implications for sustainable forestry practices more broadly.

OVERVIEW

To better streamline the breadth of literature revolving around silvics, stand dynamics, stand density, and vegetation management in boreal forests, this literature review will be divided into subsections, listed as follows:

1. Economic Demand and Silvics of Boreal Forests in Ontario
2. Stand Dynamics of Boreal Forests
3. Density Management in Boreal Forests
4. Density Management Methods
5. Vegetation Management in Boreal Forests
6. Vegetation Management Methods
7. Vegetation Management Strategies for Reducing Herbicide

SELECTION OF SOURCES

To identify relevant sources for review two key databases were used. Sources for the literature review were queried using both the Lakehead University Knowledge Commons and Lakehead University OMNI Portal. Keywords relating to silviculture, renewal, density management, vegetation management, stand dynamics, silvics, and individual density and vegetation management methods were used to query articles. Emphasis was placed on finding and using peer-reviewed journal articles from within the last 30 years. Articles which studied subjects within the Ontario boreal forest were prioritized. However, acceptance was given to governmental publications, older publications that provided solid foundational background on the subjects, and publications with relevant findings which did not occur in the province of Ontario (but still within the boreal region). Articles from outside the boreal region were used sparingly and only when relevant connections could be made. Relevant literature was also sourced from within literature used in other peer-reviewed articles. It should be understood that this methodology may have limitations in allowing for all relevant knowledge to be parsed. It also has the potential to create a bias on this topic. Because of this, this literature review is by no means an extensive dive into all the nuances of silvics, density and vegetation management, and the future of forest management. It is, however, meant to continue the conversation about the importance of responsible, adaptive, sustainable forest management in the Ontario boreal forest.

ECONOMIC DEMAND AND SILVICS OF BOREAL FORESTS IN ONTARIO

ECONOMIC USES OF COMMERCIAL TREE SPECIES

Ontario has many tree species that are considered merchantable and thus are harvested and processed for industrial and consumer products. The exact species that are considered merchantable vary by region depending on local regulation, market demand, proximity to a processing facility, and forest management objectives. For example, Resolute Forest Products is currently the largest operating forest products company in Northwestern Ontario, with five operations including the Thunder Bay pulp and paper mill, the Thunder Bay Sawmill, the Thunder Bay pellet plant, the Ignace sawmill, and the Atikokan sawmill (Resolute Forest Products 2021). The Thunder Bay pulp and paper mill is a Northern Bleach Softwood Kraft (NBSK) pulp mill, which requires a steady supply of long-fibred black spruce (*Picea mariana* (Mill.) B. S. P.) and jack pine (*Pinus banksiana* Lamb.). The Thunder Bay sawmill requires black spruce, jack pine, and white spruce (*Picea glauca* (Moench) Voss.) to manufacture dimensional lumber. The Thunder Bay pellet plant utilizes the sawing waste from the Thunder Bay sawmill and manufactures wood pellets for the Atikokan biomass-fired generating station (Maria Church 2017). The Ignace and Atikokan sawmill process black spruce, white spruce, jack pine, and balsam fir (*Abies balsamea* (L.) Mill.). Thus, the main merchantable boreal tree species, directed by the market demand in the Thunder Bay region are black spruce, white spruce, jack pine, and balsam fir.

Paper birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.) are also harvested in this region, though they are sent to other operations throughout northwestern Ontario. However, stands with large components of poplar that lack veneer-grade stems are usually underutilized (Prevost et al. 2022). This creates compliance problems as contractors struggle to meet residual tree requirements and transportation costs become uneconomical to send low-grade poplar farther from the stand. Birch suffers the same utilization issues, with the majority of the non-veneer-grade harvest being used for firewood. For these reasons, researching and innovating new efforts to increase the utilization of these species would be wise.

BLACK SPRUCE

Black spruce comprises the largest proportion of the total growing stock of Ontario's forests at 30% of the provincial growing stock (MNRF 2016). It is harvested at the highest rate compared to any other tree species in the province, with 40% of the annual total volume harvested being comprised of black spruce. As a staple of the forest industry in Ontario, its prevalence in the landscape in a constant fibre supply is important, as is the quality at the individual tree level. The current black spruce working group has much of the volume in the 0-30 and 71-120 year age classes (MNRF 2016). There is a decrease in the volume from the 31-80 year age classes, possibly indicative of poor renewal practices or natural disturbances occurring in the past. This outlines the importance of a comprehensive and sustainable silvicultural program to ensure a constant fibre supply. Black spruce has a high prevalence in the mid-to-north region of

Ontario, from Sudbury in the south to the Hudson's and James Bay coast in the northern region of the province (MNRF 2016).

Black spruce grows in a variety of climates, though in central Canada a cold, humid to subhumid climate is typical, and annual temperatures are in the range between 7° C in the southern areas too -11° C near the tree line (Viereck and Johnston 1990). Much of the precipitation in the black spruce range comes from snow accumulation in the winter months, in which dormancy can range from 225 days to 305 days. Black spruce grows on a variety of different site types, but generally in lowlands with wet organic soils (Viereck and Johnston 1990). Other soil types include deep humus clays, loams, sands, course tills, and boulder fields or shallow soil over bedrock. Ontario black spruce sites and the sites around the lake states are typically peat bogs formed from ancient glacial lakebeds. The primary economic use of black spruce in North America is pulp (Nesom and Guala 2004). Other uses include use in part of the manufacturing of SPF lumber (Spruce, Pine, Fir), though its relatively small size leads it to be used in smaller lumber such as studs and small-scale building products. Black spruce wood can be used for biofuel (Nesom and Guala 2004), generally in the refined pellet form when mixed with pine and fir.

Black spruce is typically slow growing, but its growth rate is dependent primarily on the location within its range and the quality of the site. Black spruce in even-aged stands tend to grow at a faster rate than those growing in uneven-aged stands (OECD 2010). This is why organic soiled sites that were originally stocked with pure black spruce are generally regenerated again as pure stands after harvest. The slower growth rate of black spruce results in it taking twice as long to reach breast height when compared to other boreal tree species like trembling aspen, paper birch, and jack pine

(Vasiliauskas and Chen 2002; OECD 2010). Black spruce, however, are longer-lived species and can commonly reach 200 to 250 years old on lowland sites, and 70 to 100 years on upland sites.

The slow growth, long-living potential, and shade tolerance of black spruce place it as a late successional species in the boreal forest, compared with earlier successional species like jack pine and trembling aspen. On organic soils, black spruce grows in pure stands, and on mineral soil, it will typically grow in mixed stands (OECD 2010). In mixed stands it is commonly associated with paper birch, trembling aspen, white spruce, tamarack, or balsam poplar. On upland dry sands and gravel in Ontario black spruce will regenerate under jack pine. This association with jack pine has also allowed black spruce to have intermediate tolerance to fire, with semi-serotinous cones allowing for post-fire regeneration (OECD 2010). Balsam fir and white spruce will succeed black spruce in the absence of fire. There are six commonly occurring subtypes of black spruce: a) black-spruce feathermoss, b) black spruce lichen, c) black spruce-dwarf shrub, d) black spruce sphagnum, e) black spruce speckled alder, and f) black spruce sedge (Eyre 1980).

JACK PINE

jack pine is a small- to medium-sized conifer that is native to the northern forest region of the United States and Canada, and it is a staple species within the boreal forest region in North America. In Canada, jack pine is considered the most widely distributed tree (MNRF 2014), and in Ontario, it is the second most prevalent tree, second to black spruce, at 11% of total growing stock volume (MNRF 2016). It is also the second most important economic tree species in Ontario, making up 25% of the annual harvest. Its wide availability lends to its commercial success in the pulp and lumber industry. The current jack pine working group has an abundance in the 11-40- and 71–100-year age classes (MNRF 2016). There is a shortage in the 41–70-year age class, possibly due to previous mismanagement and natural disturbance on the landscape. With its prevalence in the forest industry, researching to advance the management of jack pine is in the best interest of forest managers. Advanced silvicultural practices in density and vegetation management can ensure that jack pine prevalence continues to be high on the Ontario boreal landscape.

In Ontario, jack pine is distributed in the mid-region of Ontario, from near the Algonquin highlands in the south, to the southern extent of the Hudson's Bay Lowlands in the North (MNRF 2016). The region experiences a similar climate to that of black spruce. In the mid-Ontario region, jack pine is considered an important commercial species for its diverse uses, including the manufacturing of pulpwood and dimensional lumber (OECD 2010), as well as its uses in biofuel pellet manufacturing. jack pine typically grows on sandy soils, though it can also be found on loamy soils, thin soils over granites, over limestones, on peats, and soil over permafrost (Rudolph and Laidly 1990). In the great lakes area, jack pine generally grows on the level to rolling sand plains characteristic of glacial, fluvial, or lacustrine geological activities. It can also occur on eskers, sand dunes, and rarely on rock outcrops or bald rock ridges (Rudolph and Laidly 1990). jack pine is an early successional and pioneer species that germinate on mineral soil exposed from major disturbances, most commonly fire. As a result, it is often naturally found in pure and even-aged stands, and in many cases, the only dominant species for very large contiguous areas in the boreal (Rudolph and Laidly 1990).

Jack pine will commonly grow in mixed stands with other boreal species. Canopy tree associations of jack pine in the Ontario boreal forest include trembling aspen, paper birch, balsam fir and black spruce (Rudolph and Laidly 1990). Balsam fir and black spruce act subordinate to and are suppressed by jack pine due to its relatively early onset of fast growth while trembling aspen and paper birch are coordinated as early successional species. jack pine exists within six distinct subtypes: a) jack pine-balsam fir-black spruce (SPF), b) jack pine-feather moss, c) jack pine-sheep laurel, d) jack pine-sphagnum, and e) jack pine-lichen (Eyre 1980).

WHITE SPRUCE

White spruce is a common species used in the production of dimensional lumber and is also used in the manufacturing of pulp and paper (MNRF 2016). It is not quite as economically dominant as black spruce and jack pine and only accounts for 4% of the growing stock volume in Ontario. However, the management of white spruce as a prevalent tree species in the boreal is important to diversify both the forests in which we derive forest products and the feedstocks in which we use to produce forest products. The current white spruce working group has the most coverage in the 0–40-year age classes (MNRF 2016). In the recent past, white spruce has become a preferred species for reforestation due to the wide range of sites it can readily establish on (OECD 2010). It is the most planted tree in Canada. The increased obligation for forest managers to restock harvest stands and the increased frequency of planting have likely played a role in the proliferation of younger age classes of white spruce.

White spruce is commonly found in southern to northwestern Ontario, and the only lack of prevalence is found in the Hudson’s Bay Lowlands (MNRF 2016). The climate that white spruce experiences in Ontario are the same as black spruce and jack pine, characteristic of long, cold winters and short, humid summers. White spruce has extreme variability in the climate and conditions it can grow in, which has gained it the moniker of a “plastic” tree species (Nienstaedt and Zasada 1990). White spruce has historically readily established on postglacial landscapes, as well as those of lacustrine, marine, and alluvial origin (OECD 2010). Though it has a large range of conditions it can grow in, white spruce can have very specific moisture and fertility requirements to grow to its full potential, mainly found to grow well on well-drained, fertile soils.

Because white spruce covers such a broad ecological niche, it has species associations with most of the other boreal tree species (Nienstaedt and Zasada 1990). Common associations include white spruce-jack pine, white spruce-balsam fir, white spruce-black spruce, white spruce-aspen, white spruce-paper birch, and white spruce-tamarack. White spruce is a mid-successional species and takes an important role in the successional structure of many forest stands. When establishing the following disturbance, white spruce will establish in even-aged stands, either pure or mixed with other pioneering species (Nienstaedt and Zasada 1990). It will be succeeded by less tolerant species and remain in the understory for 50-70 years but will eventually emerge. The most common agents of disturbance that affect white spruce in the boreal are fire and insect defoliation, namely the spruce budworm.

BALSAM FIR

Balsam fir is a common commercial tree species in Ontario used for pulp, paper, and lumber products, and is one of the three staple species in the manufacturing of SPF forest products (MNRF 2016). Balsam fir accounts for 5% of Ontario’s annual growing stock volume and is 2.5% of Ontario's annual forest volume. The balsam fir working group in Ontario has a normal distribution from 0-120+ years, with most of the growing stock in the 51-100 year age classes (MNRF 2016). Because balsam fir is a tolerant and late successional species, it will stay suppressed and clumped in the understory of earlier successional forest types like poplar/aspen and jack pine (Frank 1990). In the absence of disturbance in the boreal, balsam fir may become the climax community which persists until replaced by disturbance.

Balsam fir is commonly found across the majority of Ontario, from the southern Niagara region to the southern extent of the Hudson's Bay Lowlands in the north (MNRF 2016). As a result, the climate within the range is similar to those of the other common boreal tree species, characterized by long, cool winters and short, hot, and humid summers (Frank 1990). Balsam fir grows on many organic and inorganic soils,

common boreal tree species, characterized by long, cool winters and short, hot, and humid summers (Frank 1990). Balsam fir grows on many organic and inorganic soils,

mostly of postglacial origin. Soils that are of neutral pH generally provide the optimum growth potential for balsam fir (Bakuzis and Hansen 1965; Frank 1990). Slow growth occurs on poor sites, such as shallow soil, gravelly sands, and lowland organic sites (Fowells 1965; Frank 1990).

Balsam fir is commonly associated with black spruce, white spruce, paper birch and trembling aspen in the boreal forest (Frank 1990). Balsam fir is strong at persisting in the understory and is considered a very tolerant species. However, the amount of tolerance is relative to the quality of the site. Balsam fir in pure stands often grows in clumps, so intraspecific competition is common, and the result is poor overall growth rates of individual trees (Frank 1990). Other competition can occur from tolerant hardwoods that persist in the understory.

PAPER BIRCH

Paper birch, or white birch, is a species mostly used for firewood and home heating, though it is also used for veneer, pulp and paper, and some specialty products like panelling, tongue depressors, and ornamental items (Parish 1948; Safford et al. 1990). The sap can be used for syrup like sugar maple (*Acer saccharum* Marsh.), though the amount of sap required for a reasonable yield makes it a time-consuming and expensive process (Parish 1948). Paper birch accounts for only 8 percent of Ontario’s growing stock, and 3% of the harvest volume as a low-merchantability species (MNRF 2016). The current working group has a normal distribution, with the bulk of the area in the 51–110-year age classes.

In Ontario, paper birch is widespread in distribution across the province, but where prevalence is the highest is between the Algonquin Highlands in the south and the southern extent of the Hudson’s Bay lowlands in the north (MNRF 2016). The climate in which paper birch grows is very variable, one of the most variable of all the merchantable tree species. Paper birch can also grow on almost any site, from pure rock boulder fields to flat lowland swamps (Safford et al. 1990). The most optimal sites, however, are deeper, well-drained, ashy, acidic, mineral-heavy soils, also known as spodosols. This leads to paper birch being a very effective pioneer species that grows effectively after heavy site disturbance. Paper birch has even been found as the most likely species to colonize difficult-to-restore lands, such as mine spoils, poor and abandoned agricultural fields, and areas with very poor air quality (Perala and Alm

1990). The ability of paper birch to grow effectively on ashy soils could lend its usefulness as a crop tree for biofuel use, as the ash by-product could be effectively used as a soil amendment in birch plantations. This will be discussed further in the upcoming section exploring novel methods and alternatives for vegetation management.

TREMBLING ASPEN (POPLAR)

Trembling aspen (or simply aspen or poplar) is the most widespread tree in North America and thus is a staple of the boreal tree species (Perala 1990). In Ontario, it accounts for 22% of the province's growing stock volume, second only to black spruce (MNRF 2016). However, although second to black spruce in prevalence, the annual harvest volume of aspen is less than half of that of black spruce, at just 18%. The working group of aspen in Ontario has significant numbers in younger years and even more in older years, with a decrease in the 41-60 year age range (MNRF 2016). Trembling aspen utilization has been increasing in Ontario but the ability for adequate utilization is largely dependent on mill presence in the region and market demand. Because of its ability to readily establish and dominate sites after disturbance (Perala 1990), aspen is seen as a serious source of competition for the establishment of more utilized and valuable species (SPF).

Aspen is widespread across Ontario and has moderate to high occurrence in most of the province (MNRF 2016). Like paper birch, the climatic conditions aspen grows in are varied. In Ontario, aspen will be present in every climatic extreme on either end of the temperature range, given that the site is free of permafrost (Perala 1990). Aspen will also grow on a variety of soil types ranging from shallow to deep, rocky to deep loam and sands, and even on heavy clays (Perala 1990). Coarse sands of glacial outwash and shallow rocky outcrops will generally not promote good growth and development. The same issue occurs on sandy and pure sand soils because of low moisture and nutrients, and on heavy clays because of poor drainage (Perala 1990). The best aspen sites will have well-drained silty-clay soils. Because aspen is an early and competitive colonizer its main forest type is pure aspen (Perala 1990). However, aspen is also associated with all the previous boreal tree species as both a minor or major part of a mixedwood stand.

COMPARISON OF COMMERCIAL TREE SPECIES

Table 1 compares the different factors of each of the six commercial boreal tree species, as described above. They are compared on their percentage of the total growing stock and harvest volume in Ontario, their economic uses (from most common to least), their distribution in Ontario, their shade tolerance, site tolerance, optimal site type, and management considerations. This is not an exhaustive comparison but will provide a quick reference to better understand the importance of some of these species and emphasize proper management. One major observation to note is how prevalent in distribution and variable in site tolerance birch and aspen are in Ontario’s Area of the Undertaking. Despite this, birch and aspen have the lowest utilization of all the other forest species. This raises questions about why birch and aspen have not received heavier consideration from other non-timber uses that could increase their utilization. This will be explored briefly in the vegetation management portion of this literature review.

Table 1. A comparison of multiple species factors for commercial species in the boreal forest.

Species	Ontario Growing Stock/Harvest Volume (%)	Economic Use	Ontario Distribution	Shade Tolerance	Site Tolerance	Optimal Site	Regeneration/Management Considerations	Literature
Black Spruce	30/40	Pulp, Lumber, Biofuel	Mid to north regions	Very	Variable	Lowland wet organic soils	Protect establishment from competition, winter harvest, CLAAG or clearcut, regenerate pure or with SPF stand types	MNRF 2015 MNRF 2016 Viereck and Johnston 1990
Jack pine	11/25	Pulp, Lumber, Biofuel	Mid to north regions except HBL	Intolerant	Glacial, fluvial, lacustrine, rocky outcrops, eskers, dunes	Upland sandy soils	Protect establishment from competition, ENDR clearcutting, regenerate pure or with SPF stand types	MNRF 2015 MNRF 2016 Rudolph and Laidly 1990
White Spruce	4/unknown	Pulp, Lumber, Biofuel	South to north regions except HBL	Mid	Postglacial landscapes	Well-drained, fertile soils	Protect establishment from competition, ENDR prescribed fire after clearcut systems to prepare a seedbed, regenerate pure or with SPF stand types	MNRF 2015 MNRF 2016 Nienstaedt and Zasada 1990 Abrahamson 2015
Balsam Fir	5/2.5	Pulp, Lumber, Biofuel	South to north regions except HBL	Very	Variable	Neutral pH sites	Allow growing in the shade of overstory species. Can be considered secondary merchantable species in spruce/pine dominant stands.	MNRF 2015 MNRF 2016 Frank 1990
Paper Birch	8/3	Firewood, Veneer, Composites, Pulp	Widespread	Mid to Intolerant	Variable	Deep, well-drained, mineral-heavy soils, spodsols.	Regenerate from seed readily with seed tree/shelterwood systems. Regenerate from stump sprout with clearcut.	MNRF 2003 MNRF 2016 Safford et al. 1990 Perala and Alm 1990
Trembling Aspen	22/18	Veneer, Composites	South to north regions except HBL	Intolerant	Variable	Well-drained silty-clay soils	Low-intensity fires, clearcut root suckering, seeding from seed tree	MNRF 2003 MNRF 2016 Perala 1990

STAND DYNAMICS OF BOREAL FORESTS

Stand structure is the interaction between both live and dead trees within a stand (Brassard and Chen 2006). These interactions are important for the overall dynamics within a forest ecosystem. The boreal forest has a limited number of tree species compared to many diverse forest types across the globe. Because of this, the dynamics that occur between these species and the communities they make up are predictable. Brassard and Chen (2006) note that several main factors can affect the composition of species within the forest. This includes fire frequency intervals and fire intensity affecting stand succession, landscape configuration and surficial deposits affecting soil composition across the landscape, and small-scale disturbances which partially affect succession in stands and are important in the absence of stand-replacing fire. This section will focus on these three factors and how they relate to the species assemblages that may grow on certain sites. This will solidify the notion that instead of fighting against nature, forest managers should work with nature by using stand dynamics to their advantage.

STAND SUCCESSION

Stand succession is a process which occurs temporally as the age of a stand increases and changes occur to the stand species composition (Bergeron and Dubic 1988). Succession will occur until a disturbance event resets the temporal progression of the stand. Boreal forest colonization follows the format of autogenic succession where the soil is present and species colonize an area after a disturbance of varying intensity. This secondary succession is accepted as following the Connell-Slayter model of ecological succession (Connell and Slatyer 1977). This model of succession considers three models, each exhibiting how a particular process of succession affects the original pioneer species. The three models are the facilitation model, the inhibition model, and the tolerance model. These models are not mutually exclusive and can often have overlapping boundaries and nuances (Pickett et al. 1987; Kenkel et al. 1997).

In the facilitation model, the succession is controlled by the vegetation on the site (Pickett et al. 1987). It assumes that species which have qualities suitable for the pioneering of a site will be able to colonize and facilitate the growth of later cohorts (Connell and Slatyer 1977). These qualities include effective dispersal methods, seed dormancy, and rapid growth rate. The colonizing species will grow together in an early successional cohort until crown closure. Because of this, the facilitation model evolves to have drawbacks for the species which benefit from it initially. Once a cohort has colonized the site, its fast growth rate and subsequent crown closure will limit the availability of resources for future cohorts. This changes the conditions of the site to be unconducive to early successional species, and they become more likely to facilitate later successional species which can tolerate the low light levels and limited resources (Connell and Slatyer 1977). An example of a facilitation species would be jack pine colonization of a site and facilitating black spruce growing beneath.

In the inhibition model, the competition is so strong that the growth of other species cannot be facilitated (Connell and Slatyer 1977; Pickett et al. 1987). Other colonizing species will also be unable to establish because the colonizing cohort will alter the site through rapid growth (Connell and Slatyer 1977). This will eventually close the canopy and also make the site unconducive for the growth of shade-intolerant species. An example of this is fire-origin jack pine which can often establish so thick that the stand will stagnate and another cohort cannot grow beneath it (Weth 1999).

The tolerance model differs from the facilitation and inhibition models in that the colonizing cohort does not facilitate nor inhibit the growth of a later cohort, but instead tolerates the competition (Connell and Slatyer 1977). The species on the site will be the most efficient at exploiting the limited resources on the site (Pickett et al. 1987). In the tolerance model, species which come later are tolerant of the growth characteristics of the colonizing cohort. An example of this would be balsam fir, which will stay dormant in the understory, tolerating low light conditions. These species typically can persist into a climax community, in which the dominant species replace or reduces the pioneer species through persistent competition (Connell and Slatyer 1977).

LANDSCAPE CONFIGURATION

Which succession model occurs is dependent on the species which are present at the site during colonization. the landscape configuration of a stand determines the types of species which will colonize after disturbances and will influence successional pathways in the stand (Brassard and Chen 2006). The landscape configuration is heavily dependent on the surficial deposits and soil structure. The soil structure of a site will also dictate soil richness, or poorness, and thus can alter species occupancy on a site. Mesic sites will tend to have mixedwoods established on them, with a heavy emphasis on trembling aspen (Gauthier et al. 2000; Brassard and Chen 2006). Hydric and xeric sites will tend to host conifers, like spruces and firs (Bergeron and Dansereau 1993; Timoney 2003; Brassard and Chen 2006). Jack pine and paper birch tend to establish readily on drier rocky or sandy sites (De Grandpré et al. 2000; Gauthier et al. 2000; Timoney 2003; Brassard and Chen 2006). Black spruce will readily grow on acidic sites while other species won’t, such as lacustrine bog-type sites (Parisien and Sirois 2003; Brassard and

Chen 2006)). Because these sites dictate the species that occur, they also dictate the process of succession and will affect the disturbance regimes which occur.

DISTURBANCE REGIMES

Fire frequency, which is the number of occurrences of fire, within a defined forest unit, within a defined timeframe, is one of the most important factors in determining the structure of forest stands (Bergeron and Dubic 1988). Stand-replacing fire is the dominant disturbance in North American boreal forests (Brassard and Chen 2006). The time since the last stand-replacing fire is reflected through the composition of a stand, as this will dictate the temporal stage of succession the stand is in. Fire can have a profound effect on the structure of the proceeding forest. Some instances of fire can affect areas of the forest so large that they will alter forest management due to the dynamics which occur in stands afterwards.

For example, in 1980 a major fire event occurred in Northwestern Ontario altered the stocking of the Black Spruce Forest and its future management strategy. This fire, known as Thunder Bay 46, resulted in 126,747.7 ha of forest being consumed by stand-replacing fire (Natural Resources Canada 2002). The main outcome has been a significant age class imbalance, and at the time of publishing of the 2001 FMP, 7% of the Black Spruce Forest’s productive forest was in the 41–60-year (near merchantable) age class, and 16%, approximately 110,000 ha, was in the 21–40-year age-class due to the 1980 disturbance (Ratz 2004). Much of this forest was comprised of jack pine-dominated stands, which tend to self-replace as a fire-endemic species (Burns and Honkala 1990). In the 2001-2021 Black Spruce Forest FMP the jack pine working group accounted for 25% of the total forest area, 16% of which was overmature (80+ years) and 63% was less than 40 years as a direct result of this fire and similar large fire events (Ratz 2004). Stands regenerating after this fire also exhibit very high stem densities of anywhere from 15,000 to 30,000 stems per hectare, which have a negative effect of stand stagnation and low productivity (Weth 1999).

Though fire is more pervasive and obvious because of its cataclysmic nature, non-fire disturbance also plays a very large role in gap dynamics and species assemblages in boreal forests. In Canada, insects and other non-fire disturbances are responsible for a larger area of disturbed forests than fire every year (Kneeshaw 2001; Bergeron and Fenton 2012; Natural Resources Canada 2022a). Insects can be as devastating as fires, like the spruce budworm (*Choristoneura fumiferana*) which commonly destroys buds and defoliates large swaths of trees in the eastern boreal forest (Morin et al. 2009; Bergeron and Fenton 2012). However, the disturbance patterns to stands that have experienced insect outbreaks are very different from fire. Fire tends to destroy all of the standing trees immediately (Perera et al. 2009; Bergeron and Fenton 2012) while insect outbreaks will kill trees over a longer period and create a patchier structure, and some or most of the stand may persist after the disturbance due to the selective targets of the insects (Rossi and Morin 2011; Bergeron and Fenton 2012). Because of the different dynamics of each disturbance, it can be expected that stand-replacing fires will reset succession back to the colonization of a site, while insect and other non-fire disturbances will alter a site in a way that gap dynamics will be the main successional pathway. This alters the vegetation dynamics on a site and determines the species composition. Small-scale disturbances may also play a role in succession through small gap openings, mineral soil exposure, and the killing of older age-class trees to allow younger cohorts to grow.

Fire and non-fire disturbances are not mutually exclusive in the boreal and have dynamics which affect each other. Fire disturbances play a significant role in the severity of insect outbreaks. In the case of spruce budworm, longer fire intervals create forest conditions of older aged stands that are more vulnerable to host budworm infestations (Bergeron and Fenton 2012). Insect outbreaks can also weaken stand structure and make trees more susceptible to wind events. Wind events can either be smaller intermediate disturbances that affect a single tree or groups of trees and create gap dynamics (Bergeron and Fenton 2012), or they can be large, stand-replacing events which decimate hundreds of hectares (Kuuluvainen 2004). Thus, all disturbances are a factor in the succession and dynamics of forest stands. This emphasizes the importance of having silvicultural strategies to affectively manage stands after a fire to ensure the success of future stocking. This includes density and vegetation management strategies, which will be discussed further.

DENSITY MANAGEMENT IN BOREAL FORESTS

THE BASICS OF STAND DENSITY MANAGEMENT

Stand density management in forests is the process of controlling resource competition by regulating the density of growing crops based on various management goals (Sharma and Zhang 2007). Density management is arguably one of the most important components of silvicultural sustainable forest management as it allows managers to alter the growing stock based on their long-term management objectives (Long 1985). It can provide high economic crop yield while still maintaining sustainability targets for regenerating forests. The management occurs at both the early and mid-silvicultural stages, either during stand establishment with initial spacing or with intermediate cutting treatments called thinnings. A stand is thinned multiple times in the basic stand density treatment model, and each time it is thinned to its lower limit after being able to grow at its upper-density limit (Long 1985). The determination of the lower and upper-density limits is the subject of complex stand dynamics and biological factors. Generally, these limits are based on size-density relationships, such as those described in Reineke’s Stand Density Index (SDI) (Reineke 1933). Reineke’s SDI is an antiquated concept by today's standards because it is nearly 100 years old, though it is still considered a useful tool to generally estimate the required density for targeting stocking levels in stands despite its universality (Shaw 2006).

Stocking refers to the quantitative measure of merchantable occupancy within a stand based on specific management objectives (Vanderschaaf 2013). Stocking is a relative term, and when comparing stands of different densities (Reineke 1933). In a set of stands with the same characteristics (species, site type, age, average diameter), the stand with the highest density is considered 100% stocked. Reineke’s SDI is used to estimate the stocking of even-aged stands based on the logarithm of the quadratic mean diameter (DBH of the tree representing the average basal area) plotted against the logarithm of the stem density, measured as trees per hectare (Shaw 2006). This relationship creates a linear outer limit that represents the maximum, or full density that a stand can reach before it is considered fully stocked. Beyond this line, tree size cannot increase unless the density of the stand is decreased (Forrester et al. 2021), either through self-thinning or management intervention.

WHY LOWER STAND DENSITY?

Stand density is an important factor in the merchantable growth of a forest stand. Lowering the stand density through initial stem spacing or pre-commercial thinning increases the average diameter growth (MAI) after treatment by extending the period of free growth before crown closure and suppression occur (BC Ministry of Forests 1999, pp. 11-14). Increased diameter growth will increase tree size and log diameter at the point of harvest. Larger tree and log sizes lower transportation costs because they increase per-tree utilization and decrease waste (BC Ministry of Forests 1999, pp. 25)

Stand density is not just related to the economic value and merchantability of the stand and can have implications on ecological objectives too. A study by Hedwall et al. (2019) found that an increase in density in forest stands can contribute to a decrease in forest diversity by lowering species richness in the understory of the stand. Findings surmised that even though biomass and species richness was increased by shade-intolerant broadleaf trees being mixed with conifers, the crowding due to the increased density of the forest can at a point revert these benefits due to resource filtering (Hedwall et al. 2019). If biodiversity values are considered as part of forest management, as they should be with any sustainable management plan, this has implications for the balance between economic fibre supply and ecological management objectives. For this reason, lowering stand density should be considered along with other management methods for mixedwood forests.

The exact target of stand density is dependent on several factors like species, SDI, site productivity, and management objectives. There are, however, some general findings for ranges of numbers to use as targets for certain species. For example, jack pine stands that are overstocked above 4,950 stems per hectare should be cleaned (pre-commercial thinned) to improve the growth and development of the stand (Rudolph and

Laidly 1990). These high densities should be lowered optimally to between 2,000 and 3,000 stems per hectare to take advantage of increased growth potential. If stands are not thinned and left to grow in high densities, they can eventually reach their maximum density and stagnate (Benzie 1977). Beyond this point, stem diameter growth becomes very slow, and treatment is required to increase productivity in the stand again. Self-thinning of jack pine can aid in decreasing these densities naturally, though if Reineke's (1933) model is considered it would not be optimal to rely on self-thinning for diameter management objectives because it will occur at a slow rate, only to perpetually maintain the stand at its maximum stand density. This is why prescriptive treatments are useful for increasing the productivity and economic viability of stands.

SELF-THINNING

Trees growing in competitive environments demand a certain level of resources and growing space. As these plants grow, this demand becomes larger, and at a certain point, the availability of resources on a site will no longer be adequate to support growth further (Pretzsch and Biber 2005). When these resources cannot sustain the demand of the density of trees, the number of trees in each unit area will begin to decrease via mortality. Self-thinning and the increase in resource demand with tree growth occur from intraspecific (local) competition, that is, competition within a species of trees (Kenkel 1988).

For example, jack pine is a species that is known to self-thin (Kenkel 1988). Mortality will occur within even-aged stands that are over-density, resulting in a decrease of density over the development of the stand, which follows the self-thinning rule proposed by Reineke (1933) and later re-evaluated by Yoda et al (1963). The 1988 study by Kenkel aimed to observe the pattern of self-thinning in jack pine and determine how much intraspecific competition affects self-thinning by testing the random mortality hypothesis. The random mortality hypothesis suggests that the distribution of live trees in a stand has little difference from what you would expect observing the same stand in a previous state due to the inherent nature of mortality being random, or stochastic. The findings of the study indicate that the random mortality hypothesis does not apply in this case and that there is a pattern within the self-thinning of jack pine due to intraspecific competition. In short, as density increases, mortality will be more common as the stand self-thins to regulate the competition load. This pattern results in a model represented by differential mortality rather than random mortality.

Kenkel identifies two important competitive phases within jack pine's development through this study. The first phase is coined as “an early scramble phase” where individuals experience two-sided (symmetrical) competition for soil, water, and light nutrients until depletion. In high-density stands, this results in aggregate groups of young trees being shaded out by individuals that have become larger. This then develops into the second phase of competition in later stages of stand development coined the “contest phase”. In the contest phase, light becomes the limiting resource, and one-sided or asymmetrical competition occurs, where large individuals within the canopy disproportionately gain access to light resources while understory trees are suppressed and eventually die (Kenkel 1988). The result of these interactions over the development of even-aged jack pine stands that have decreased in density as it ages.

THE EFFECTS OF STAND DENSITY ON TREE CHARACTERISTICS

Although lowering stand density increases the per-tree merchantable volume (Buckman 1964; McClain et al. 1994; Weiskittel et al. 2011; Moulinier et al. 2015), the alteration of growth rates of trees through silvicultural treatment can have differing effects on wood quality, tree characteristics, and overall stand volume (Cown 1972; Zhang et al. 2006; Morris et al. 2011; Tong and Zhang 2011). A 2004 study conducted by Kang et al observed the effects of initial spacing on wood density, fibre, and pulp properties in jack pine. Within their study, Kang et al (2004) found that increasing the initial spacing and thus lowering stand density had significant positive and desirable effects on the stand. The main effect on yield was an increase in the proportion of trees in the stand from smaller to larger diameter classes.

Wood density, however, was affected differently. It was found that wood density decreased with a decrease in the density of the stand. This finding can be interpreted twofold. Lowering the density of the wood can be seen as reducing the quality of the wood, as denser woods are desirable for their increased strength (Blankenhorn 2001). However, a decrease in the density of the wood can also signify an increase in the growth rate of the tree (Kennedy 1995), indicating a shorter time to merchantability and thus a shorter rotation. This can be a desirable outcome even when sacrificing some material strength. The decrease in stand density was also found to increase the number of extractives (Kang et al 2004). This was hypothesized to be due to the lower stand densities allowing for a higher concentration of foliage, which is key to metabolizing extractives. Total lignin content was also increased in stands with lower densities (Kang et al 2004). This can also be considered undesirable due to an increased lignin content complicating the pulping process and creating weaker pulp (Davidsdottir 2013, pp. 723-727). Kang et al (2004) also found this with further analysis showing that pulp yields were greater in stands at higher stem densities.

A study by Zhang et al. (2021) found similar results. Wood density decreased opposite of the increase of initial stand spacing in a black spruce trial. Radial and volumetric shrinkage also decreased with wider spacings, while volumetric shrinkage increased. The overall per-tree shrinkage may not be a large issue and could even be considered negligible, but it could affect usage properties in certain applications which require specific timber properties. However, the outcome of decreased rotation time may be of greater importance to forest managers depending on their management objectives. The diversified use of individual boreal species as either pulp wood or sawlog, along with bolstering pulp yield and strength with multiple species (SPF), may motivate managers to choose lower densities as a management strategy to focus solely on increased fibre yield coming off the landbase. Additionally, focusing on intensive forest management and conducting more intensive silviculture and harvesting in smaller areas, especially in the face of a declining landbase due to conservation and societal values (Lautenschlager 2000), will put pressure on forest managers to produce more with less.

STAND DENSITY MANAGEMENT DIAGRAMS

Managers can use Stand Density Management Diagrams (DMD) to guide the management of even-aged, single-species stands. These diagrams were first described by Drew and Flewelling (1979) and were created to quantify the effects of tree density on growth and allow the direction to be taken in managing future stands. DMDs are based on the SDI and the rule of self-thinning initially proposed by Reineke (1933) and later adapted by Yoda et al. (1963). The relationship can be visually represented by a line of -3/2 slope which is created when tree volume is plotted against stand density on a logarithmic scale (Farnden 1996). Therefore, at any stand density, a management diagram can be used to hypothesize the theoretical maximum average size of a tree. As density increases, mortality increases, so there is an optimal density at which tree size will be maximized, and beyond this point, the stand will produce a lower yield (Farnden 1996). Density management diagrams can also be used to estimate dominant tree height, relative density, and average or quadratic mean DBH in forest stands at a given density.

Figure 1 displays a density management diagram for jack pine in Eastern Canada (Sharma and Zhang 2007). The y-axis of the diagram represents the volume of the tree and additionally has logarithmic scales for the dominant tree height (HT) This is compared with the x-axis which is tree density. Both axes are on a logarithmic scale. Diagonal lines also represent the relative density (RD) of the stand. The same is represented for quadratic mean density (QMD). The values of each of these metrics are determined where lines intersect one another. For example, using Figure 1, at a theoretical density of approximately 1350 stems per hectare, the average tree volume will be 0.10 m^3, the dominant tree height will be 12m, QDBH will be 14cm, and RD will be 0.40.

DENSITY MANAGEMENT METHODS

Multiple theories and experimental studies have now been discussed regarding the ideology behind density management and its utility in boreal forests. Now it is important to outline the current methods that are used to manage density in boreal forest stands. The main methods include pre-establishment treatments and thinning treatments. These methods have been well established with years of literature proving their efficacy

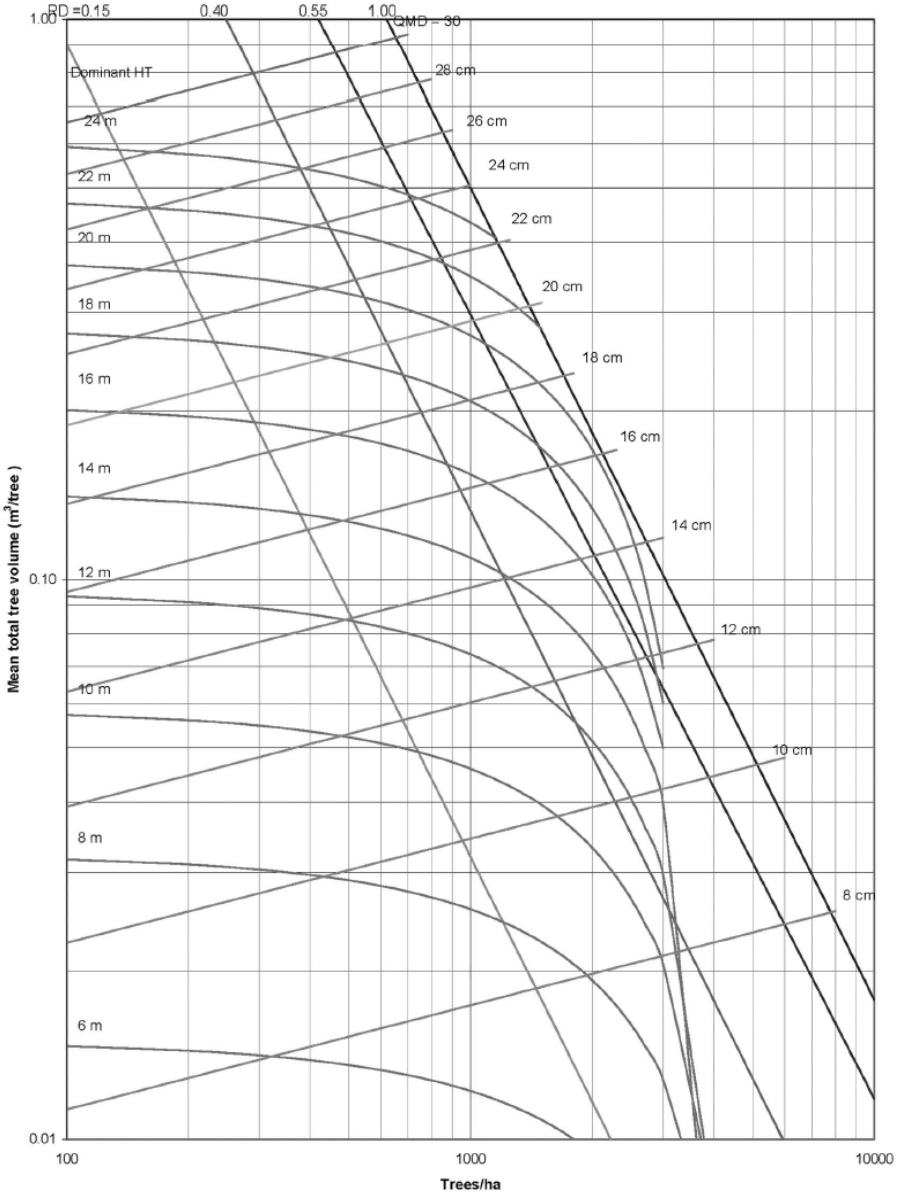

Figure 1. A stand density management diagram of jack pine in Eastern Canada, from Sharma and Zhang (2007).

This represents the basis for density management practices which are currently used in many boreal forest stands in Ontario. Figure 2 displays the general silvicultural thinning management timeline of a forest stand (MNRF 2003, 2015). The initial cleaning stage occurs right after establishment and will typically involve herbicide applications, so it will be considered vegetation management and will be outlined further.

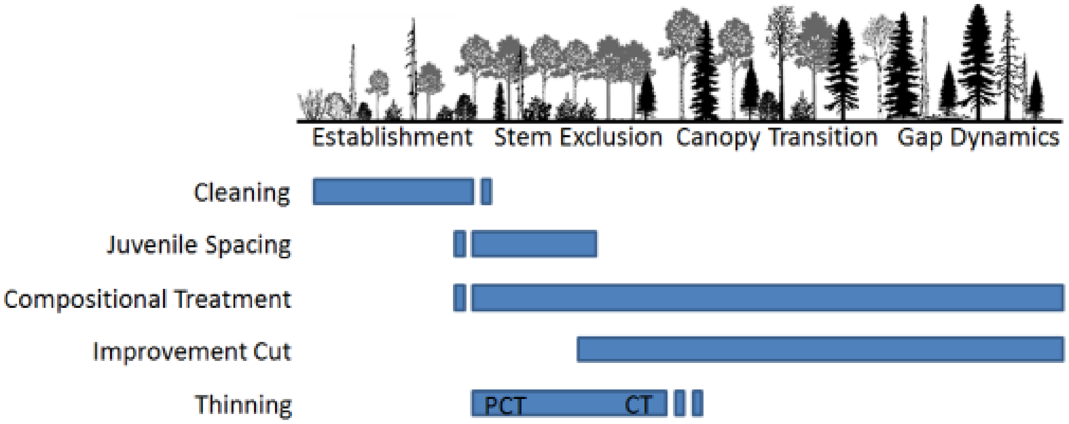

Figure 2. The timeline of thinning treatments in a forest stand, from stand establishment to gap dynamics. From MNRF 2003.

Initial Spacing

When compartments are to be regenerated artificial planting is a commonly used treatment method because of the container stock's competitive advantage and the ability to set the density of the establishment (Duryea 1992). Planting is useful because it can be suited for the most competitive sites, site prepared or not (MNRF 2015). Stand density and structure can also be controlled for management purposes with planting. In Ontario. Jack pine, white spruce, black spruce, white pine, and red pine are commonly planted in boreal regions (MNRF 2015). Planting is typically done in rows and each tree is evenly spaced to the specifications of the forest management plan.

If establishing a stand with planting, it should be initially spaced to a target that satisfies the management objectives. A study of black spruce, white spruce, and red pine initial spacings in a legacy 1950 Thunder Bay spacing trial by McClain et al. (1994) demonstrated the economic merits of increasing initial spacing and proactively lowering the stand density when establishing a stand. After 37 years of growth, the study reassessed trials planted at 1.8 m, 2.7 m, and 3.6 m initial spacing and found that DBH, live crown length and crown width all exhibited a significant increase with increasing initial spacing while there was a decrease in height. McClain et al. (1994) also found that the total and merchantable stem volume of each tree increased with increased initial spacing, although the stand volume per unit area decreased. Because of the higher value of timber which could be extracted to the increased merchantable stem volume, it is considered that a decrease in volume per unit area is an acceptable loss when considered economically.

Another study in northern Minnesota measured a jack pine pre-commercial thinning trial for changes in diameter across various treatments (Buckman 1964). The study compared the growth of no-thinning with thinning to square spacings of 1.2, 1.8 and 2.4 m. The site had been direct seeded by jack pine, like the site this thesis is observing, and the stand was averaging 32,100 stems per hectare at 5 years. Results from a twenty-two-year remeasurement found the average diameter at breast height (DBH) of trees to be 9, 10, 13 and 15 cm for the control, 1.2, 1.8 and 2.5 m spacings respectively. These results are indicative that pre-commercial thinning of overstocked stands is a good management practice to increase the merchantable volume of a stand. In just twenty-two years the increase of the DBH by 6 cm is a significant gain in merchantability. The preliminary increase in the value of the stand is already worth the investment.

Post-establishment Treatments

Treatments post-establishment, but before crown closure occurs will manipulate the density, composition, structure, and quality of the future stand (MNRF 2015). These include juvenile spacing, compositional treatments, and improvement cuts. Juvenile spacing removes undesirable trees in a juvenile stand to free up space for desirable trees (BC Ministry of Forests 1992). Some target species will be removed during this and thus interspecific competition will be decreased. Cut trees have no commercial value so they are left on the site as downed woody debris (DWD). Trees will be cut to allow a specific spacing between crop trees, which will equate to a total stem per hectare density on the overall stand (BC Ministry of Forests 1992).

Compositional treatments are not used to directly manage stand density, but they will reduce the overall density within a stand. These treatments are applied to alter the proportion of species in a stand based on management objectives which dictate a target species composition (MNRF 2015). Common treatments are manual or chemical, and removed stems can be merchantable or non-merchantable depending on species and age. Improvement cuts are like compositional treatments as they do not directly target density, but lowered density is an added value. Improvement cuts remove undesirable trees of any species in favour of stand development (MNRF 2015). This can be done as a single tree or a group and may be done to release suppressed artificial or natural trees.

Thinning

Thinning is a complex topic in forestry and an entire series of books could be written on the nuances and intricacies of it. Thinning is the compromise between maximum growing space per land area and maximum growing space per individual tree (Ashton and Kelty 2018, p. 461). In the simplest terms, thinning is the partial removal of the canopy to meet economic objectives in the stand through lowered stand density, thus producing larger stems for timber production. There are several basic principles that thinning should follow. First, thinning is only done once a stand is released and beyond the establishing stages of treatment (seedlings, saplings, poles) (Ashton and Kelty 2018, pp. 461-462). Second, to maximize the efficacy of thinning, managers should take care to ensure that openings created in the canopy are not too large (Ashton and Kelty 2018, p. 461). Canopy openings that do not close in sufficient time after growth will invite understory species to infiltrate. The structure of thinning operations is dependent on the stage of the stand and what managers expect to get out of a stand. Pre-commercial thinning is considered an investment treatment on a stand because there is no economic gain immediately seen from it (Ashton and Kelty 2018, p. 462). It is generally done earlier on in the rotation of the stand just after crown closure has occurred (MNRF 2015). Stems are left on the site as downed woody debris. Commercial thinning is done later in the development of the stand (Figure 2) (MNRF 2003, 2015). Because of this, the size of a tree that is cut during a commercial thinning enables it to be a profitable treatment, producing a net income for the trees cut.

Pre-commercial thinning can also be used to release desirable understory species from a stand while increasing the merchantability of the overstory cohort. A study of boreal mixedwood stands in Alberta, conducted by Bjelanovic et al. (2021) found that pre-commercial thinning was effective at decreasing the density and increasing the yield of both the overstory and understory. The study thinned aspen to 0, 1000, 2500, and 5000 stems per hectare, and had an unthinned control (Bjelanovic et al. 2021). The unthinned plots had greater mortality than the thinned plots. After eight years, the aspen diameter was increased by thinning, but height had no difference. Planted spruce survival was not affected by aspen density, but the spruce diameter and height growth increased with aspen thinning intensity and time since treatment. The final yield estimation results suggest that a heavy pre-commercial thinning to 1000 aspen per hectare will increase merchantable volume without lowering the aspen volume (Bjelanovic et al. 2021). Lighter to moderate thinning averaging approximately 2500 aspen stems per hectare did not have similar gains in merchantability for both aspen and spruce.

A study by Prévost and Gauthier (2012) had similar results for overstory. The study observed the effect of unthinned, 2.5, 3.0, and 3.5 m aspen spacing on both the retained overstory aspen and the understory balsam fir. It found that over ten years, the pre-commercial thinning increased aspen diameter increment by 66-85% and the basal area increment by 234-326%. Understory balsam fir greater than 1 m was favoured with the pre-commercial thinning, as height and crown growth were two to three times that of the control. Regenerating balsam fir was not favoured with the pre-commercial thinning, however. Prévost and Gauthier (2012) suggest that, in addition to increasing the merchantable volume of the stand, pre-commercial thinning can be used to limit complete softwood conversion in the early stages of stand development.

A somewhat abstract and controversial method of pre-commercial thinning is aerially thinning with herbicide. This method is different from typical chemical applications as it is done in the growing season before conifer buds have hardened off. A 1999 study by Weth applied Vision glyphosate and Release Tripoclyr at varying concentrations on an overstocked jack pine stand. The stand was treated by helicopter with a thru valve boom that has three-meter swath spacing. One year after application each treatment was measured using a series of established sample plots, and there was an apparent decrease in live tree density on the site, as every other three-meter strip was killed. The site was later remeasured in 2004 (KBM Forestry Consultants 2005) and the stem density had reduced by 50% across the treatment area. Black spruce had begun infiltrating the understory so total stem density was increasing, though they did not provide as much of a competitive threat and the canopy appeared to be released from the competition. While seemingly effective, this type of treatment would likely be seen as socially irresponsible. Herbicide is under strict watch from the public eye, and using herbicide application on crop trees would likely receive poor reactions from environmental groups. However, it does contribute to the knowledge that supports the pre-commercial thinning release of stands.

A study on structure changes in a 22–30-year-old white spruce stand after commercial thinning was conducted by Omari (2016). The study explored changes in tree growth and deadwood dynamics. The study had an unthinned control and three 40% basal area removal treatments, each with a varying degree of deadwood left on the site. After three years the basal area increment and crown diameter were larger in the thinned stands compared to the unthinned. The increased growing space from thinning increased tree growth through heightened crown leaf area (Omari 2016). This increased the photosynthetic rates of the foliage in the lower crown. This study suggests that commercial thinning is beneficial even as the stage increases with age. The increased growing area allows tree diameter increment to increase and per-tree yield is higher as a result.

VEGETATION MANAGEMENT IN BOREAL FORESTS

In the Ontario boreal, there are several species which provide steep competition for resources with commercial tree species. Several characteristics of these species give them an edge over crop trees. The main categories of these competitive species include graminoids, forbs, small shrubs, and tall shrubs and trees (Bell et al. 2000; Balandier et al. 2006). Graminoids or grasses, such as blue-joint grass (*Calamagrostis canadensis* (Michx.) Beauv.) have very dense root systems that can uptake water and nutrients, which provides them with a high growth rate and ability to outcompete neighbouring species for light, water, and nutrients (Lieffers et al. 1993). Forbs, which are small shrub-like plants that are not grasses, like fireweed (*Epilobium angustifolium* L), have a high aerial dominance over establishing tree species due to their quick growth (Balandier et al. 2006). Their dense cover can also shade out establishing stock, which leads to severe competition for light resources.

Small shrubs, like blueberry (*Vaccinium angustifolium* Ait.) and raspberry (*Rubus idaeus* L. var. *strigosus* (Michx.) Maxim.) are like forbs in that their dense coverage and ability to overtop and crowed out crop trees will negatively impact establishment by limiting light resources (Balandier et al. 2006). Tall shrubs and trees, most notably paper birch and (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.), can have the most profound competitive advantage over the establishment of crop trees due to their fast growth, and their demand on resources reduces the growth potential of surrounding species (Balandier et al. 2006). The competition of these trees can persist even after establishment as they grow into the canopy and become codominant stems.

Unfortunately, these species are not commercially viable and pose a threat to the structure of managed forests. Because of this, in the interest of retaining the health of forests and optimal growth of commercial species, these competitive species must be suppressed or removed. Limiting the effect of these competitive species on forests is a major management challenge. Several strategies of varying intensities can be used to manage competing vegetation. These include pre-establishment methods like site preparation, and cleaning methods like chemical, manual, and mechanical. Some novel methods limit chemical means like biological control methods, spot herbicide applications, and increased utilization of competing species.

VEGETATION MANAGEMENT METHODS

SITE PREPARATION

Site preparation describes the range of silvicultural treatments which prepare the planting or seeding area for the establishment of a stand (Ashton and Kelty 2018, p. 137). The treatments are made to slash, competing vegetation, the forest floor in general, and the soil. The main goal is to ensure the successful establishment of the stand by increasing microsite suitability and decreasing competing vegetation. Managing slash is an important part of site preparation, but it is less involved with vegetative management and more to free up planting space in a harvest compartment (Ashton and Kelty 2018, pp. 137-138). Because of this, I will forgo getting into fine details of slash management and focus specifically on mechanical and chemical site preparation to reduce vegetation management. Reducing competing vegetation in an establishing stand is important to provide regenerating stock with the highest chance of survival. Eliminating competing vegetation is typically not possible, but temporarily suppressing them until regenerating stock is large enough to overcome the competition is typically feasible (Lowery and Gjerstad 1991).

Mechanical Site Preparation

Mechanical site preparation is generally done to remove debris after harvesting, but it is also effective to control existing or expected vegetation likely to affect regenerating stock (Lowery and Gjerstad 1991). Mechanical site preparation methods most effective for vegetation management include shearing, trenching/bedding, and mounding. Shearing is done to remove standing vegetation from the compartment before planting (Lowery and Gjerstad 1991). A sharpened blade is horizontally mounted on a prime mover (i.e., a skidder) just above the soil surface to sever stems and stumps and discard them into a swath. After shearing, the slash is managed with piling or raking, and the side is cleared of competing vegetation for planting (Lowery and Gjerstad 1991).

From personal experience working in the Ontario boreal forest, mounding and trenching have been by far the most common mechanical site preparation treatment for directly planted compartments. Mounding is the artificial heaping of soil to increase planting spots and elevate a microsite above the competition (Sutton 1993). It is an emulation of a natural phenomenon called pit and mound micro-topography (Londo and Mroz 2001). The advantage of the elevated microsite is increased drainage and height dominance of the mound (Orlander et al. 1990; Lieffers et al. 1993). The saturation below the mound can limit the germination of competing species while the surface dehydration on top of the mound can prevent seed germination. Because mounding is generally done to create a proper microsite, the vegetation management properties are a value-added effect that makes mounding an attractive site preparation option (Sikström et al. 2020). Trenches offer a similar advantage to mounding, as a trench can be considered a continuous, linear mound (Sutton 1993). In this case, trees can be planted all along the trench in suitable microsites, and the elevation above any competing species that might germinate provides a competitive advantage for regenerating stock.

Chemical Site Preparation

The most prolific chemical site preparation treatment is herbicide application, which chemically targets broadleaf vegetation to clear a site for the establishment of conifers (Ashton and Kelty 2018, p. 404). In Canada, the typical herbicide treatment is aerially sprayed (or broadcast) Glyphosate, which is the active ingredient in the forestry-tailored Vision® herbicide (Thompson and Pitt 2003). Glyphosate is the most effective and widely used herbicide, with wide-ranging applications in agriculture, horticulture, land clearing and forestry (Duke and Powles 2008). It works by inhibiting a critical growth enzyme in a plant's shikimate pathway called 5-enolpyruvyl-shikimate-3-phosphate (EPSPS). The shikimate pathway is a linkage of the metabolism of carbohydrates to aromatic compounds (Duke and Powles 2008).

Glyphosate is topically sprayed either aerially or in a ground-based treatment (Ashton and Kelty 2018, pp. 443-449) and is absorbed through the surfaces of plants via diffusion and is translocated from shoots to roots via the phloem (Duke and Powles 2008). It is not inherently clear why glyphosate is so effective at killing plants, but it is known that all higher plants are susceptible to its effects, so it is considered a non-selective herbicide (Duke and Powles 2008). Other common herbicides used in chemical site preparation include Triclopyr (Garlon®), Dicamba (Vanquish®), and Hexazinone (Velpar®) (Lambert et al. 2020). If complete removal of all vegetation on site is desired, these are usually applied during the early summer growing season for uptake from all vegetation on site. If the protection of advanced conifer regeneration is important, then after the late summer conifer bud dormancy is the most optimal time to apply (Lund-Hoie 1985; Tanjung 2001).

Pre-treating a site with chemical site preparation is more effective than application a year after planting, according to Wood and Von Althen (1993). Their study evaluated the effects of vegetation management pre- and post-planting on white spruce transplants and black spruce transplants and container seedlings. The study found that with or without chemical site preparation, there was a significant improvement in height growth, stem diameter, and seedling vigour over the control of no treatment (Wood and Von Althen 1993). However, the sites that had a chemical site preparation treatment, which removed 95% of the woody sprouts shrub, and herbaceous competition, exhibited significantly improved survival and growth over the sites only treated after planting. The study also suggests that applying a chemical site preparation treatment will increase the soil temperature over a control site and will thus increase the likelihood of root growth (Wood and Von Althen 1993). This is because the chemical site preparation removes the competing vegetation and allows sunlight to reach the soil in a competition-free zone.

Prescribed burning, also called broadcast burning, is another form of chemical site preparation that is effective at removing competing vegetation. In the boreal forest, very hot broadcast fires can be used to manage debris, expose mineral soil, control competing ground vegetation and release nutrients (Ashton and Kelty 2018, p. 150). These fires should be hot but should also quickly burn off fuels and not be allowed to smoulder deep into soils, as this may cause damage to the sensitive soil layers and impede growth. Prescribed burning can also be used in combination with other treatments, such as herbicides (Ashton and Kelty 2018, p. 150) Because prescribed burning is not done often on crown forests because of public perception and risk, I won't go into much further detail. Introducing fire onto the landscape more would be a benefit to ecological based forest management, but with the multiple stakeholder-based models of forest management in Ontario, it is difficult to ensure all parties are on onboard with prescribed burning.

CLEANING AND WEEDING

Chemical

Chemical cleaning/weeding is similar in principle to chemical site preparation with herbicide. Because of this, I will not go into exhaustive detail about chemical cleaning methods, but I will briefly discuss why the application of herbicide to conifer is possible. The basic principle of chemical cleaning is that a stand is either aerially or ground-based with a broad-spectrum herbicide during the stand establishment period after trees have been planted or seeds sown (Ashton and Kelty 2018, pp. 443-449). During certain periods of the year, conifers are not susceptible to the defoliation effects of herbicide, depending on the application rate (Sutton 1978; Newton and Knight 1981; Tanjung 2001). This is because conifers are only susceptible to herbicide during periods of shoot growth and elongation (Radosevich et al. 1980; Tanjung 2001) For this reason, the herbicide is applied after the conifer dormancy period begins, which is typically late summer after the next year's buds have formed and hardened off (Lund-Hoie 1985; Tanjung 2001). This occurs when the conifer sends lignin up the shoot to surround the bud, which creates a waxy coating that will not absorb the herbicide. Because broadleaf seedlings are unable to create this resistance at that point in the year, they become more susceptible to the herbicide and can be selectively cleaned out of the stand with a chemical application (Tanjung 2001).

Conifer release with herbicide is more effective at suppressing competing vegetation for longer than motor-manual brush cutting, but both have a similar effect on crop tree growth (Mallik et al. 2002). The Mallik et al study compared a single application of glyphosate, a multiple application of glyphosate, and a motor-manual brush-cutting treatment to control competing plants in a seven-year-old jack pine stand in northwestern Ontario. The single and multi-glyphosate applications were 90% effective at removing competing vegetation, whereas the brush saw treatment was only initially effective at lowering competing stem density (Mallik et al. 2002). Proceeding the brush-cutting treatment the competing stem density began to rise again as suckers and sprouts revegetated the site. However, both the herbicide and manual treatment were more effective than the no-treatment control and resulted in an increased height and basal diameter of the jack pine. There were no significant differences in target species growth between the three treatments (Mallik et al. 2002).

Manual and Mechanical

For the sake of brevity, this report will consider manual and mechanical cleaning and weeding methods to be of the same category. Manual methods are generally low-impact hand tool methods, including motor-manual brush sawing (Ashton and Kelty 2018, pp. 449-450). Mechanical methods are typically implemented that are affixed to prime movers and cover large areas efficiently (Ashton and Kelty 2018, pp. 450-451). Manual and mechanical methods of vegetation management are on the more expensive side of treatments compared to chemical methods (Camenzind 2002), but they are also perceived as the best alternative vegetation management treatment by the public because of their perceived low ecological impact (Wagner et al. 1998).

Manual methods are commonly used on high value, established stands experiencing high competition in regions in which herbicides are not common or not socially acceptable. Quebec, for example, began reducing its use of chemical herbicides for vegetation management in 1995, and in 2001, the use of herbicides on crown forests became outlawed (Thompson and Pitt 2003). Thus, Quebec has long recognized the need for effective alternative vegetation management methods and has strongly looked to manual and mechanical brushing practices to supplement the shortfall caused by an herbicide moratorium. Mechanical release of forest plantations is the main method currently used to control competing vegetation in Quebec (Thiffault and Roy 2011). The growth response of conifers following chemical release can be near replicated when moderate competition is a factor by using mechanical release methods (Jobidon et al. 1999; Thiffault and Roy 2011).

However, the mechanical release may not be as effective on sites where competitive species are rapidly growing and crown closure can occur quickly. Shade-intolerant species, like aspen/poplar which have carbohydrate stores within their roots, can effectively and aggressively sucker from stumps and roots following a brushing treatment (Schier et al. 1985). In this case, due to the aggressive nature of their competition, successive treatments may be required to control poplar to mitigate detrimental effects on crop trees (Thiffault and Roy 2011). Successive treatments will increase the associated cost of management, which can make manual practices unattractive when compared to chemical treatments. There are several novel methods to control this stump sprouting and reduce the need for successive treatments. These will be discussed further in the proceeding section that outlines the future of vegetation management for reducing herbicide use in the Ontario boreal.

Brushing is a method of vegetation management, considered a cleaning treatment, where competing stems are cut at the stump, typically with brush saws. Brushing will reduce shading from overtopping vegetation but may require successive cuttings due to stump and root sprouting of hardwood species (Ashton and Kelty 2018, pp. 449-450). Because of its low impact, brush cutting is highly accepted among the public (Wagner et al. 1998) and can be done at times of the year when herbicides are not able to be used (Ashton and Kelty 2018, p. 450). Timing of brushing treatment application is important to ensure that stump and root sprouts have less vigour to regrow. Cutting in the early growing season will limit sprout growth because of depleted carbohydrate reserves in the roots (Ashton and Kelty 2018, p. 450). A study by Wayne et al. (1999) studied the effect of season and height of cut on immature aspen stems/ The study had cut treatments in fall, winter, and summer at 10, 25, 50, 75, and 100 cm above ground level (Bell et al. 1999). The results suggest that the vigour of aspen regeneration can be limited if manual cutting is done in June and July and the cuts are slightly higher at 50 to 75 cm. Conversely, cutting in the fall at 25 cm produced the most growth in regenerating stems (Bell et al. 1999). This study suggests that some degree of planning is required when considering brush sawing as a vegetation management strategy.

Girdling is a vegetation management method that is similar in practice to brushing but it involves disturbing the cambium of a tree so the tree stresses and eventually dies, rather than completely severing the stem (Camenzind 2002). The result is the interruption of the downward flow of nutrients to the roots. Girdling reduces the vigour of hardwood suckers compared to cutting treatments and allows for a longer window of release (Thorpe 1996; Wiensczyk et al. 2011). Only girdling the stem and not severing it ensures that the plant will be stressed but will not signal a re-sprouting.

Thorpe (1996) notes that spring and summer are the best times to girdle, and fall treatments are not as effective but can still be used. This is like the results of the brushing time and height of cut findings from Bell et al. (1999). A unique type of girdling employs the use of backpack-mounted diesel or propane torches which apply a flame to a stem for 5 to ten seconds (Camenzind 2002). This kills the cambium and has the same effect as girdling with less worker fatigue from bending over.

Another interesting method of manual vegetation management is bend and break. While not novel, the use of the bend and break method, also known as stem snapping, has had limited use on forests in Ontario. Most of the literature surrounding bend and break comes from a 2002 report by Camenzind, which reviewed the efficacy of several brushing treatments conducted in the Bulkley Timber Supply Area in the Skeena Region of British Columbia. Along with manual and mechanical brush sawing and girdling, bend and break was seen as a promising method of decreasing broadleaf vegetative competition in conifer plantations. The treatment is applied to stems that are too small to girdle, such as newly established plantations after clear-cutting. Because the stem is broken but the cambium is still intact, the vegetation can still translocate nutrients through the stem to the roots (Camenzind 2002). The effect the bent stem has is that it reduces the height of the tree by forcing it to continue growth in a horizontal position. Eventually, stress will cause the top portion of the stem to die, and sprouts will grow from the still-living lower stem (Camenzind 2002).

VEGETATION MANAGEMENT STRATEGIES FOR REDUCING HERBICIDE

While herbicide may be the most effective vegetation management treatment in the silviculturist's toolbox, it is also the most controversial. Out of the typical proposed methods of alternative vegetation management, aerially spraying herbicide ranks the lowest, with spot-spraying herbicide coming in as a close second (Wagner et al. 1998). Today, a plethora of environmental groups and public advocates are very vocal online and in Local Citizen's Committees about their views on herbicide use in crown forests, with "*stop the spray*" campaigns continuously gaining support. For this reason, proposing alternatives which limit the use of herbicides is necessary. Manual cleaning methods have long been the alternative, but they are time-consuming and expensive. Unique alternatives like biological control methods, spot-application methods, and hardwood utilization methods are increasingly being implemented by forest managers.

UTILIZATION OF BIOLOGICAL CONTROL METHODS

The aggressive sprouting of poplar species after manual cutting has proven to be a management obstacle for converting hardwood dominant stands to a higher conifer composition. Topological treatments for cut stumps can limit the sprouting from stumps for a certain amount of time and increase the likelihood of growing stock regeneration success. One method of this is a biological control method involving the fungus *Chondrostereum purpurpeum* (Pers.) Pouzar is applied to broadleaf stumps directly after cutting to reduce sprouting (Camenzind 2002). *Chondrostereum purpurpeum* is a basidiomycete, which is a fungus that inoculates through a wound in the stem and kills the plant through cambial necrosis (Rayner 1977; Becker et al. 2005).

A 1990 study by Wall examined the effect of *Chondrostereum purpurpeum* on the stump sprouting of red maple, sugar maple, yellow birch, paper birch, pin cherry, trembling aspen, and beech. The stumps were treated immediately after being trees were felled in the spring and summer. The result of this study was that the stumps developed sporophores within two years and the number of stump sprouts was greatly reduced when compared to the inoculated control. Unfortunately, the speed of stump inoculation varied widely between species tested, which could result in it being difficult to get consistent results when applying this method to multiple species in a compartment.

Another study by Becker et al. (2005) which examined the efficacy of *Chondrostereum purpurpeum* on red alder stumps had similar results. The study found that 92% of the inoculated stumps died in the first year and 100% by the second. Becker et al. (2005) note that the biological treatment was as effective at suppressing sprouting as an herbicide treatment. It is also worth noting that the use of the biological treatment caused no unwanted effects on non-target crop trees.

A study by Pitt et al. (1999) found that the isolate of *Chondrostereum purpurpeum* and the target species have a large effect on the efficacy of the treatment. The study treated speckled alder, red maple, and aspen with two different isolates of *Chondrostereum purpurpeum* and compared the results with a no-treatment control and triclopyr treatment. Pitt et al. (1999) found that while the herbicide had the greatest efficacy after two growing seasons, the *Chondrostereum purpurpeum* still allowed for a significant decrease in stump sprouting compared to the control treatment. The alder was the most successful at a 72% reduction in stem volume. This was followed by aspen at 35% and red maple at 32%. The study suggests that even though there is a slight efficacy decrease from herbicide, biological control can still be a viable option over not treating competing vegetation at all.

LIMITED APPLICATION OF HERBICIDE

While broadcast herbicide application is effective, the public generally has a negative view of the practice which puts pressure on forest managers to find alternatives which reduce reliance on herbicide (Little et al. 2006). Herbicide reduction is part of the compliance and requirements for certification for many forest sustainability certification programs such as the International Standards Organisation (ISO-14001) and the Forest Stewardship Council (FSC) (Little et al. 2006; Forest Stewardship Council 2019). The aim for many of these certifications is to outright stop the use of herbicides in forestry operations, but in the meantime, the focus is on reduction strategies using other treatment options. Because broadcast applications are non-selective, the perception is that this herbicide will get into unwanted areas and can destroy sensitive ecological processes and impact soil in ways not originally intended (Little et al. 2006). Thus, alternatives which reduce the amount of herbicide used in forests are welcomed.

The alternative to these broadcast applications is spot treatments which target singular stems. These include options like stem injections and chemical/mechanical girdling, cut-surface treatments, basal-bark treatments, soil applications, and ground-based foliage applications (Ashton and Kelty 2018, pp. 410-412). Stem injections and chemical girdling are used for larger trees, generally greater than five centimetres in diameter and they can be used both for release and pre-commercial thinning operations (Ashton and Kelty 2018, p. 410). The treatment requires one or a series of cuts to be made into the stem of the tree, and then a water-dissolved herbicide is sprayed into the cuts to kill the cambium and phloem, essentially suffocating the tree from receiving sugars from the stem. Tools used for this method can be hatchets with automatic spraying nozzles or injectors that can be stabbed into the base of the tree (Ashton and Kelty 2018).

A 2011 study by Bried and Hecht found that chemical girdling and injection methods were effective at killing competing aspen and preventing resprouting. The methods used were chainsaw frilling (girdling with a chainsaw and applying herbicide), drill and fill (drilling a series of holes in the stem and filling with herbicide), stem injection and basal bark spraying. The chainsaw frill and drill and fill methods were the most effective at 95% effective killing of treated aspen less than 18.3 cm and 23.6 cm respectively (Bried and Hecht 2011). The stem injection and basal bark spraying methods were less effective, but still 95% effective at killing aspen less than 10 cm and 16.5 cm respectively. This study suggests that these treatments could be used at varying stages of the competition in a stand to provide effective removal of competing vegetation.

The application of herbicide to cut stumps is also an effective method to suppress stumps and root sprouting after harvest or cleaning treatments. A study by Johansson (1988) tested the effectiveness of attaching a sprayer to a hydraulic brush cutter which sprayed a mixture of glyphosate and imazapyr on stumps while cutting. The study was conducted on ten-year-old birch and fifteen-year-old aspen. The results of the study indicated that the cutting and surface spraying treatment was quite effective at killing the competing vegetation while limiting exposure of herbicide to the soil and surrounding vegetation (Johansson 1988). These results suggest that larger-scale treatments could be used, such as mounting a sprayer directly to a large, prime mover-mounted hydraulic shear or hot saw felling head. Although, applying herbicide to a high RPM spinning blade may not be as effective, as the herbicide may dissipate quickly off the blade due to centrifugal force and not treat the stump effectively (Wayne Bell, pers. comm., March 8, 2023). In this case, the most effective treatment would likely be herbicide application from a backpack sprayer after cutting has taken place.

INCREASED COMMERCIAL UTILIZATION OF COMPETITIVE SPECIES

Because much of the commercial use of forest species in the Ontario boreal relies on conifer, hardwoods tend to be underutilized and thus are seen as weeds, waste, or firewood. Most of Ontario’s boreal forest product processing facilities are pulp and paper mills and sawmills which rely heavily on a conifer dominant feedstock, specifically SPF (Figure 3). This creates a utilization issue for hardwoods and pure conifer is desired when regenerating as a result. Economically this makes sense, but ecologically it is troublesome to be removing large amounts of hardwood from the landscape. This is especially true on sites that are suitable for pure hardwood or mixedwood stands. However, too much hardwood becomes economically difficult because it can create a surplus of wood with no use. This is a real issue that could occur because of the increased public backlash on the use of herbicides. One unique solution to improve the utilization of hardwoods is to increase their harvest for biopower uses.

Bioenergy is produced from renewable and biological sources termed *biomass*, which is plant material that can be turned into fuel used for heating and electricity generation (Natural Resources Canada 2020). Biofuels have been around for some time now, with applications ranging from liquid biofuels to forest biomass (hog fuel) running cogeneration plants at pulp mills. Biomass sources can be nonmerchantable tree species,

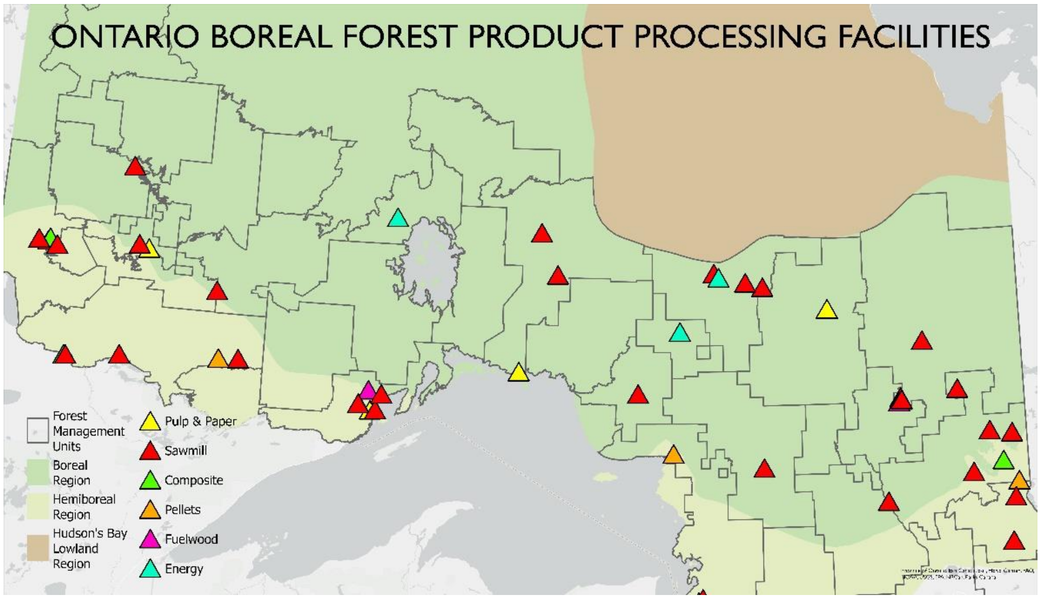

Figure 3. The locations of forest processing facilities in the Ontario boreal forest. Most of the facilities are sawmills with few scattered pulp and paper operations, which focus heavily on the continuous feedstock of SPF species. Adapted from (Brandt 2009; MNRF 2021, 2023; Natural Resources Canada 2022b

stand-thinning refuse, harvest residuals, salvaged disturbance trees, or trees specifically grown to create biomass (Natural Resources Canada 2020). Bioenergy can be created from biomass in thermal, biological, or mechanical conversion processes which make a wide range of products (Bridgwater 2006). Thermal conversion processes include pyrolysis, which creates bio-oil and fuel gas, gasification which creates fuel gas, and combustion which creates heat (Bridgwater 2006). Biological conversions are fermentation which synthesizes ethanol and digestion which creates biogas. Mechanical conversion is generally used for the creation of canola oil (Bridgwater 2006). The combustion and digestion process is of particular interest to the forestry industry, as a forest biomass feedstock is suitable, and the products can be used to fill a demand in the electricity market. One boreal tree species which has a fast growth rate and can be used to fill a demand for biofuel is poplar.

Poplar can be intensively managed in plantations for fast rotation times which can steadily supply a bioenergy operation (Sannigrahi et al. 2010). A 2008 study by Yemshanov and McKenney identified central Ontario as being a prime geographical location suitable for the creation of fast-growing poplar biomass plantations. The study recommended that Ontario be considered for smaller to medium-sized biomass processing facilities due to the high growth rate of poplar in the region. Another positive note for poplar is that it can be used to recolonize marginal lands and can be efficient in remediating and stabilizing soils (An et al. 2021). Ontario has numerous old mine sites, poorly decommissioned roads, and aggregate pits that could be used as sites for potential biomass plantations. Blending bioenergy and land reclamation could be the answer to Ontario's vegetation management issues.

One difficulty with using poplar as a biofuel is the ash by-product resulting from the combustion process to create energy. This ash is considered a waste fuel, and as such is typically landfilled. Ash has many environmental implications when disposed of in landfills (113-116). This is because biomass ash contains many elements which can alter soil chemistry (Munawar et al. 2021). There have, however, been studies which suggest that returning the ash to intensively managed poplar plantations can act as a soil amendment to return nutrients to the soil (Sannigrahi et al. 2010). A study by (Jarosz-Krzemińska and Poluszyńska 2020) found that fly ash from a biomass-fired-combustion plant met the minimum requirements for mineral fertilizers in Poland, despite a low nitrogen content. However, this low nitrogen content may bar ash from being used as a mineral fertilizer.

In Canada, AshNet is a national network of scientists, foresters, and policymakers which study the various uses of biomass ash, mainly as a soil amendment for forestry uses (Hannam et al. 2017). In 2017 in association with AshNet, Hannam et al. identified several issues that need to be addressed for utilizing wood ash as a soil amendment in forestry operations in Canada. These include understanding the regulatory process involved with changing the classification of wood ash, developing protocols for handling, and applying wood ash, improving the quality of wood ash, understanding the economics and logistics of using wood ash as an amendment, researching how wood ash can be used to emulate natural disturbances and to set up a framework for monitoring long term effects of ash applications on forested sites (Hannam et al. 2017).

The largest hurdle expected would be the regulatory process and acquiring proper permission to transport and use wood ash as a soil amendment. Hannam et al. (2016) wrote a report with AshNet exploring the regulatory framework and processes required in all the provinces and territories in Canada. In Ontario, there are currently no specific guidelines that have been developed for its use, as wood ash has not previously been extensively used as a soil amendment. To utilize wood ash in Ontario, specific permission would need to be granted from the Ministry of the Environment and Climate Change for transport as either a Solid Non-Hazardous Waste Management System or as a Soil Conditioner Waste Management System through an Environmental Compliance Approval (ECA) (Hannam et al. 2016). Then, to store or apply wood ash, an ECA must be obtained for a non-agricultural application, which would be reviewed on a case-by-case basis because there are currently no guidelines specific to using fertilizing materials on Crown Forest Land (Hannam et al. 2016). Thus, for this practice to be widely accepted in Ontario more localized studies should be conducted. These should be done in consultation with the Ontario Ministry of Natural Resources and the Ministry of the Environment and Climate Change.

CONCLUSION

Throughout this review, the importance of understanding the silvicultural practices we currently utilize as forest managers have been greatly emphasized by discussing the silvics of merchantable boreal tree species, the dynamics and structure of boreal stands, the management of density in boreal stands, and vegetation management. The silvicultural regimes used on forests have a significant impact on their health and sustainability. As managers of public forests, we have a responsibility to ensure that we are utilizing our resources efficiently and ethically. One reason why it is important to understand the current silvicultural regimes used in forestry is that they have a direct impact on the ecological health of forests. These regimes influence factors such as the density of stands, the age of the trees, and the composition of the forest ecosystem. By understanding these characteristics, forestry professionals can develop strategies that help to improve the health of forests and protect them from environmental threats such as climate change and invasive species.

Constantly reviewing current practices allows for introspection into ways these practices can be improved. Some silvicultural treatments may be better suited for certain types of forests or ecosystems than others. By understanding the strengths and weaknesses of different treatments, forestry professionals can identify areas where new concepts can be developed to enhance the sustainability of the forest industry. Current practices and their efficacies can also inform the development of new concepts that can further enhance sustainability. Concepts such as ecosystem-based management and adaptive management focus on the constant improvement of practices through application and monitoring. By understanding the current silvicultural regimes used in forestry, these new concepts can be tailored to address specific challenges and improve the sustainability of forestry practices.

The merchantable species and their silvics greatly impact silvicultural regimes and the treatments we apply to sustainably regenerate forest stands. The commercial demand of species plays a large role in dictating our target composition for regeneration. Such is the case in Ontario, where a significant reliance on SPF species for pulp and sawmill feedstock dictates our species' merchantability. This has put pressure on forest managers to increase our conifer harvest and renewal, targeting species like black spruce, jack pine, white spruce, and balsam fir. However, as stewards of the land, we must not only focus only on the most economic species individually but rather consider all species in one large ecosystem.

In this review, the silvics of the most common commercial species were discussed. This included black spruce, jack pine, white spruce, balsam fir, paper birch, and trembling aspen/poplar. Each species was compared by its percentage of the total growing stock and harvest volume in Ontario, its economic uses, its distribution in Ontario, its shade tolerance, site tolerance, optimal site type, and management considerations. This is an important discussion to have, as it provides the background and incentive for managing these species, and their specific site requirements and ecological niches are important information for forest managers to make ecologically appropriate decisions for their management.

Similar can be said for the stand dynamics of boreal forests. This was discussed in length, outlining stand succession, landscape configuration, and disturbance regimes, which all affect the dynamic movement of energy within forests, and dictate how interactions occur in the stand. Stand succession, the processes and changes which occur in the stand over a temporal scale, have a significant effect on the assemblage of species in a stand depending on what stage since establishment the stand is in. This occurs through species which follow the three models of succession, which include the facilitation model, inhibition model, and tolerance model. The landscape configuration also plays a major role in dictating what species will be able to exist on a certain site. This is a component of historical geological processes that happened across the landscape. This results in the soil structure heavily dictating the dominant species on sites. Finally, disturbance regimes are one of the most important components of stand dynamics. These include fire disturbances and non-fire disturbances like insect outbreaks and wind events. These disturbance regimes can shape stands for better or for worse, and their occurrence on the landscape requires forest managers to both integrate them and react to them within management practices.

Density management is an integral part of silvicultural management in both establishing and pre-established stands. Ensuring a stand has the most optimal density for growth is the most important thing a forest manager can do to increase the merchantability of a forest. Density management increases merchantability by removing trees from a stand and increasing the growing space allotted to each tree. This increases the mean annual diameter increment of the stand and will create trees with larger stems which are more economically desirable. This creates a trade-off between lowering overall stand volume and increasing stand merchantable volume. This can also have implications for wood quality, as faster growth can reduce desirable wood qualities like density. This practice is ideal for sawlogs but may not provide the best results for pulp wood and bioenergy feedstock. Density management methods can occur from the establishment of a stand to the end of its rotation when it is finally harvested. These methods include juvenile spacing, compositional treatments, improvement cuts, and precommercial and commercial thinning. Juvenile spacing helps the stand to establish starting at the desired density and ensures that seedlings have the appropriate growing space from the start. Compositional treatments allow managers to set a specific composition in the stand dependent on management objectives. Improvement cuts allow managers to remove trees with poor form and health, which increases the overall health and resilience of the stand, and creates high-quality trees for later harvest. Finally, precommercial and commercial thinning allows managers to maintain a constant density throughout the life of the stand. Each time crown closure occurs, a thinning can be done to enhance the growing space again and increase merchantable volume.

Along with density management, vegetation management is equally important in ensuring that compositional targets are met and that target species have the optimal space to grow freely. Because hardwood species, both trees and shrubs, are less valuable in northern Ontario, they are often suppressed to allow valuable conifer to grow. Invasive species like some grasses also provide a barrier to an establishment for many stands. There are, however, methods to mitigate this from occurring. These include site preparation and cleaning and weeding, which both include chemical and mechanical means. Chemical site preparation involves applying herbicide, usually a broadcast aerial application, over the site to clear all competing vegetation before establishment. The manual and mechanical methods of site preparation also either remove vegetation or create more suitable planting sites which resist competition. These can be used separately or in conjunction. The chemical cleaning methods also involve the application of herbicide, but this is once the stand has been established, and is done according to seasonality to ensure no damage is done to the target conifer species. Manual and mechanical methods of cleaning involve physically cutting or damaging competing vegetation to give the target established species a better chance to grow. These methods are generally more expensive and time-consuming than chemical methods, but they are generally more socially acceptable.

Because chemical vegetation management is not as well supported by the public as it once was, alternative vegetation management methods that limit the use of herbicides are increasingly becoming implemented by forest managers. This includes using biological controls, using herbicide methods with reduced herbicide and target applications, and increasing the merchantability of currently unmerchantable species. Biological control methods, like *Chondrostereum purpurpeum*, are typically applied to stumps of cut trees to induce cambial necrosis and prevent resprouting. This is an effective method, but it is very time-consuming. Using targeted and limited herbicide methods is also increasingly relied on by forest managers. This includes chemical girdling and spot application on single stumps using mechanical means which cut and apply herbicide. Finally, increasing the merchantability of previous unmerchantable species makes once undesirable species an acceptable feedstock. This includes increasingly relying on hardwoods like poplar and birch for biomass to create heat, electricity, and biofuels.

Despite the shortcomings of some alternative methods, I believe we should still be pursuing and innovating previous and new methods to reduce herbicides. As stewards of the land, foresters should strive to not only extract monetary value from the landscape but to create ecological, recreational, and societal value as well. The new age of information and connectivity dictates that public perception is one of the most important assets of any organization. Forestry should strive to maintain a positive public perception. Thus, we should be moving away from older management practices like herbicides. We should be investing in more intensive management strategies that allow for a holistic approach to forest management where benefits to both the land and society are gained. Most importantly, we should continue to consult with First Nations and Metis land managers and reintroduce Indigenous traditional ecological knowledge (TEK) back onto the landscape.

My opinion is that bioenergy is the future of forest management. Rather than fighting the ingress of broadleaf species on forest stands, we should accept that many stands will naturally transition to hardwood dominance. We should change our view on hardwood species and begin to value them as economically viable species rather than high-grading veneer quality logs and discarding the rest. With a bioenergy framework, we can use this to our advantage. We are currently at a time where we are on the balancing point and the cusp of being able to implement large-scale bioenergy projects in Ontario. However, policymakers and governmental bodies need to step up the regulatory process and begin rolling out their framework for these projects, especially regarding the use of biomass energy waste products like ash. Only after we find a way to tie these systems into a holistic cycle can we effectively use them to help sustainably manage forests.

This report was not meant to be an exhaustive list of every component of silvicultural and managing a stand from the establishment to harvest. Instead, it was created to initiate a dialogue about how we manage our forests today, and how moving forward we should manage our forests in the future. Adaptive management means that, as forest managers, we should strive to constantly improve on the work we are doing by innovating and discovering new methods of management. If we become stagnant in our commitments, we begin to fail as stewards of the forests. Just as the forests, society, economics, and the environment are constantly changing, so too must our management practices.

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