CAN DENSITY MANAGEMENT IMPROVE MARKETABILITY OF JACK PINE STANDS MANAGED FOR KIRTLAND'S WARBLER HABITAT?

By

Megan Machusko

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Forestry–Master of Science

2023

ABSTRACT

Multiple land-management agencies have implemented a management program in which ca. 1,550 hectares of high-density jack pine (*Pinus banksiana*) plantations are established annually to provide a continuous supply of breeding habitat for the conservation-reliant Kirtland's warbler (KW; *Setophaga kirtlandii*). These KW habitat plantations are established at a much higher density than a traditional forestry plantation, resulting in increased competition that results in slower individual tree growth and delayed attainment of merchantable size. Pre-commercial thinning (PCT) after stands age out of KW breeding habitat is an option to reduce densities and increase individual tree vigor and growth for the remaining years of the rotation. I initiated a small plot-level thinning experiment to assess the growth response to PCT of high-density jack pine plantations planted for KW habitat. In addition, two stands of KW jack pine plantations were put out for commercial bid to assess the costs and residual stand characteristics of operational scale PCT. The increase in diameter growth response was 16% for the 11-14 year age class, 30% for the 19-26 year age class, and 55% for the 27-35 year age class. After 25 years of age, there was a sharp drop in live crown ratio (LCR), indicating that increased competition for light results in lifting of the live crowns. Therefore, thinning as soon as possible after KW occupancy ends, and before 25 years when LCRs drop rapidly, would have the greatest impact on growth of the residual trees. Under my most optimistic scenario (2% rate of return), PCT would need to increase final harvest volume by 139% for mechanical thinning and 233% for hand thinning to break-even financially. I conclude that PCT does not appear to be financially feasible at any rate of return. Even though PCT of KW plantations may never break-even financially, the practice may be justified on public lands if it can accelerate attainment of marketability while increasing resilience to climatic warming.

This thesis is dedicated to my Grandpa August.
Thank you for always believing in me.

ACKNOWLEDGEMENTS

I would like to express my great appreciation to Dr. David Rothstein for all his support throughout this project. His mentorship and patience helped me get through this program. I sincerely thank my committee members Dr. Andrew Finley and Dr. Gary Roloff for all their helpful comments on my project along the way. I thank Daphna Gadoth-Goodman, Tina Guo, Genevieve Benson, Drew Guest, Matt Pena, and Christian Tibaudo for their assistance with field work.

I thank Jason Hartman, Keith Kintigh, Erin Victory and Tim Greco of the Michigan Department of Natural Resources for all their support and assistance with this project. I would especially like to thank Jason Hartman for encouraging me to take on this project and for giving me my start in the forestry field.

I would also like to thank my family and friends for their constant support. I am especially thankful to my best friend Leslie for reading my thesis and helping me prepare for my thesis defense. I also want to thank the MSU Department of Forestry community for all their help and support.

Financial support for this work was provided by the Michigan Department of Natural Resources Partnership for Ecosystem Research and Management (GG 200000002808) and from the USDA National Institute of Food and Agriculture (Project #MICL08505 and McIntire Stennis Project #MICL06006).

TABLE OF CONTENTS

CHAPTER 1: CONSERVATION AND MANAGEMENT OF THE KIRTLAND'S WARBLER IN NORTHERN LOWER MICHIGAN 1
1.1 **Introduction** 1

CHAPTER 2: CAN DENSITY MANAGEMENT IMPROVE MARKETABILITY OF JACK PINE STANDS MANAGED FOR KIRTLAND'S WARBLER HABITAT? 6
2.1 **Introduction** 6
2.2 **Methods** 9
2.2.1 *Plot-Scale Experimental Row Thinning* 9
2.2.2 *Stand-Scale Operational Thinning* 12
2.2.3 *Statistical and Financial Analyses* 13
2.3 **Results** 14
2.3.1 *Plot-Scale Experimental Row Thinning* 14
2.3.2 *Stand-Scale Operational Thinning* 19
2.4 **Discussion** 21
2.5 **Conclusions** 26

REFERENCES 28

APPENDIX 32

CHAPTER 1: CONSERVATION AND MANAGEMENT OF THE KIRTLAND'S WARBLER IN NORTHERN LOWER MICHIGAN

1.1 Introduction

The Kirtland's warbler (KW; *Setophaga kirtlandii*) is a migratory songbird that nests almost exclusively in young jack pine (*Pinus banksiana*) forests, mostly in northern Michigan (MDNR 2015a). Kirtland's warblers require young jack pine stands, 5-23 years old, with high stem density for breeding habitat (Nelson 1992, MDNR 2015a). The first KW census was performed in 1951, when 432 singing males were counted, and the total population was estimated at ca. 1000 birds (Mayfield 1953). The second census in 1961 counted 502 singing males and estimated the total population around 1000 birds (Mayfield 1962). During the third decennial count in 1971, only 201 males were counted, and the population was estimated at ca. 400 birds (Mayfield 1972; Byelich et al. 1985), representing a 60% decline from the previous count. After this significant decline was observed in 1971, the frequency of the census was changed to yearly in order to observe population changes more closely (Byelich et al. 1985). The particular habitat requirements of the KW have always severely limited its range (Byelich et al. 1985). Traditionally, stand-replacing fires would naturally regenerate even-aged jack pine forests across large areas, providing early-successional habitat critical to KW but fire-suppression efforts in the early to mid-1900s resulted in habitat loss that nearly drove the species to extinction (Cleland et al. 2004, MDNR 2015a).

The Kirtland's warbler was one of the first species to be listed as endangered when the Endangered Species Act of 1973 became law (USFWS 2019). To conserve this species, a Recovery Team was assembled in 1975 composed of representatives from the U.S. Fish and Wildlife Service, U.S. Forest Service, Michigan Department of Natural Resources (MDNR) and the ornithological community (Kepler et al. 1996) and a recovery plan was completed in 1976, and then revised in 1985 (Byelich et al. 1985). The goal of the recovery plan was to reach a self-sustaining KW population of at least 1000 pairs before it could be removed from the endangered species list (Byelich et al. 1985). The first step in the outline of the recovery plan was to manage ca. 51,597 hectares of state and federal land for the KW (Byelich et al. 1985). The current conservation plan, which encompasses multiple land-management agencies, outlines a management program that ensures 1,550 hectares of jack pine are established annually to consistently provide young jack pine stands that are required for KW nesting (MDNR 2015a). These jack pine plantations are created on a rotating basis to guarantee at least 12,000 ha of suitable breeding habitat in various age classes is available for nesting annually (Kepler et al. 1996; Donner et al. 2018). This program has been a success with the current KW population estimated to be more than 2,000 mating pairs, exceeding the initial goal of 1,000 pairs, and this has resulted in the delisting from the federal endangered species list in 2019 (USFWS 2019).

KW plantations are planted in an "opposing wave" pattern that includes unplanted gaps, with a high stocking density (1.5 x 1.8 m spacing) to mimic wildfire-regenerated stands that include dense areas and scattered openings (Figure 1.1; MDNR 2015a). Early studies into habitat needs of KW identified high stem densities as a feature of high-quality breeding habitat (Probst 1988). Therefore, since the early 1980s jack pine plantations established as part of the KW recovery program have been planted on an ca. 1.5 x 1.8 m spacing that equates to 3588 trees per hectare (TPH; MDNR 2015a). In contrast, traditional pine plantations in the Lake States established for roundwood production are typically planted on a 2.1 x 2.4 m spacing that equates to 1922 TPH (Benzie 1977). The current conservation plan ensures 1,550 hectares of jack pine are established annually to consistently provide young jack pine stands required for KW nesting

(MDNR 2015a). Approximately 77,500 hectares of KW plantations are required when managed on the current 50-year rotation (Gadoth-Goodman and Rothstein 2020).

Figure 1.1. Aerial view of a Kirtland's warbler jack pine plantation with the opposing wave pattern.

Natural regeneration of jack pine is inexpensive but can be unreliable, therefore the recovery team early on chose to rely on costly planting operations for the past 40 years to ensure that annual KW habitat establishment requirements were met. The establishment costs for KW plantations are high because of the need to trench, order jack pine seedlings, and pay crews to plant them by hand. At harvest, the financial returns are low because jack pine has a low average product value (MDNR 2015b). In 2021, the average sold price for jack pine pulpwood across MDNR's Atlanta, Grayling, and Roscommon Forest Management Units (core KW breeding range) was $23.74 per cord which pales in comparison to the more profitable red pine at $56.60 per cord (MDNR 2022). The costs of establishing KW plantations have outweighed the returns from harvesting for many years in the KW program (MDNR 2015a).

The specific habitat needs of the KW require jack pine to be planted at high densities, but these high-density plantations struggle to produce merchantable size trees for commercial harvest at a 50-year rotation age. These dense plantations promote competition that results in slower individual tree growth and delayed attainment of merchantable size (Nyland et al. 2016). Indeed, the high-density KW plantations established in the early years of the program are now more than 40 years of age and appear to be incapable of producing marketable roundwood products within the planned 50-year rotation (Gadoth-Goodman and Rothstein 2020). This suggests a conflict between the management goals of conservation and forest products in this system - planting at higher densities for optimal KW habitat results in delays of production of merchantable timber.

The current stand age distribution has an abundance of young jack pine and lack of mature (>50 year-old) jack pine stands in KW Management Areas. The first 40 years of the KW program relied on harvest of mature, natural origin stands or plantations that were established on a traditional forestry spacing. Forty years of intensive management for KW have now almost eliminated jack pine stands that pre-date the KW recovery program from the landscape. The only jack pine stands remaining are high-density plantations established beginning in the early 1980s. These stands are younger and the trees smaller than the mature stands that supported KW recovery in the past, this is compounded by the high density such that marketability has become a major constraint to KW conservation (MDNR 2015a).

A couple of possibilities for increasing tree growth in jack pine plantations is to plant at lower densities and use thinning in established plantations for density reduction. Jack pine plantations in Michigan with lower densities, achieved by wider spacing, were found to have a larger mean diameter at breast height (DBH) and a lower mortality rate than high-density plantations (Godman and Cooley 1970). A study by Janas and Brand (1988) in Canada found lower-density jack pine plantations led to higher merchantable volume for individual trees but at the expense of total stand merchantable volume and stem quality. Guilkey and Westing (1956) also found that decreased jack pine planting density in Michigan resulted in decreased stem quality, with trees on a 2.7 m spacing being too heavy-limbed to result in good saw timber or acceptable pulpwood. Pre-commercial thinning can also be used to increase tree growth. Intensive thinning (2212 trees/ha) of jack pine in Canada was reported to increase tree diameter by >20% and merchantable stem volume per tree by >75% (Zhang et al. 2006). Tong et al. (2005) found that pre-commercial thinning of jack pine in Canada increased the financial return, and this led to higher benefit/cost ratios in the thinned stands than the control stands.

Much of the existing literature that explores jack pine density management is from Canada. The KW Management Areas in Michigan are a unique system with KW plantations having higher densities (3588 trees/ha) than most traditional forestry plantations (2224 trees/ha) and site conditions in northern Michigan producing marginal jack pine growth compared to Canada (Zhang et al. 2006). With the recent delisting of KW and uncertainty of future funding, there is a need to reduce financial losses of the KW program. While jack pine harvested from KW Management Areas may not generate much revenue, there is still a need to produce marketable stands since management agencies must sell these stands to meet the requirements for establishing new KW habitat. Increasing revenue from commercial harvests of jack pine by growing larger and more merchantable trees or reducing establishment costs by planting fewer trees would help reduce the financial losses of the KW program. Since stand density has strong effects on tree size, tree quality and KW habitat usage, I studied the efficacy of density reductions of post-occupancy stands.

CHAPTER 2: CAN DENSITY MANAGEMENT IMPROVE MARKETABILITY OF JACK PINE STANDS MANAGED FOR KIRTLAND'S WARBLER HABITAT?

2.1 Introduction

Multiple-use forest management is essential to balance timber production and financial returns from timber harvests with maintaining wildlife habitat, particularly for sensitive species. The Kirtland's warbler (*Setophaga kirtlandii*, KW) is a conservation-reliant migratory songbird that nests solely in young jack pine (*Pinus banksiana*) forests, mostly in northern Lower Michigan (Bocetti et al. 2012; MDNR 2015a). The KW requires young jack pine stands, 5-23 years old, with high stem density for breeding habitat (Nelson 1992; MDNR 2015a). Prior to European colonization, stand-replacing fires would naturally regenerate even-aged jack pine forests, providing early-successional habitat critical to KW; however, fire-suppression efforts beginning in the early to mid-1900s resulted in loss of early successional breeding habitat that nearly drove the species to extinction (Cleland et al. 2004, MDNR 2015a). To conserve this species, a recovery plan was first issued in 1976 (MDNR 2015a), and since the early 1980s multiple land-management agencies have implemented a management program in which ca. 1,550 hectares of new jack pine plantations are established annually to provide a continuous supply of breeding habitat (MDNR 2015a). This program has been a success with the current KW population estimated to be more than 2,000 mating pairs, exceeding the initial goal of 1,000 pairs, resulting in removal from the federal endangered species list in 2019 (USFWS 2019).

Early studies into habitat needs of KW identified high stem densities as a feature of high-quality breeding habitat (Probst 1988). Therefore, since the early 1980s jack pine plantations established as part of the KW recovery program have been planted on an ca. 1.5 x 1.8 m spacing that equates to 3588 trees per hectare (TPH; MDNR 2015a). In contrast, traditional pine plantations in the Lake States established for roundwood production are typically planted on a

2.1 x 2.4 m spacing that equates to 1922 TPH (Benzie 1977). This is of concern to foresters because dense plantations promote competition that results in slower individual tree growth and delayed attainment of merchantable size (Nyland et al. 2016). Indeed, high-density KW plantations established in the early years of the program are now more than 40 years of age and appear to be incapable of producing marketable roundwood products within the planned 50-year rotation (Gadoth-Goodman and Rothstein 2020). In response, the Michigan Department of Natural Resources (MDNR) recently changed their target rotation age of KW jack pine plantations from 50 years to 70 years in an effort to achieve larger, more marketable trees at final harvest (J. Hartman, MDNR personal communication). This suggests a conflict between the management goals of conservation and forest products in this system - planting at higher densities for optimal KW habitat results in delays of production of merchantable timber.

Given apparent constraints on roundwood production imposed by high planting densities required for optimum warbler habitat, an alternative approach to extending rotation lengths would be the use of pre-commercial thinning (PCT) after stands age out of KW breeding habitat in order to reduce densities and increase individual tree vigor and growth for the remaining years of the rotation. Under such a scenario, tighter spacing during the first ca. 20 years of the rotation could be beneficial from a forest products perspective because jack pine as a species is particularly prone to reduced height growth, poor form and heavy branches if it grows with too little competition (Bella and DeFranceschi 1980; Tong and Zhang 2005). In fact, Canadian researchers recommend planting jack pine at a tighter spacing to promote good form and quality and then using PCT to boost growth (Tong et al. 2005, Zhang et al. 2006).

Pre-commercial thinning is typically recommended during the stand initiation phase because competition and growth reductions happen before self-thinning mortality begins

(Lindgren and Sullivan 2013). Gadoth-Goodman and Rothstein (2020) found that mortality from self-thinning starts to appear around age 20 years in KW jack pine stands, which suggests optimal thinning time is before 20 years of age. This aligns with jack pine recommendations from nearby Ontario, Canada, where PCT of jack pine plantations is typically suggested in the 10-15 year time frame since costs are lower and trees are still vigorous enough to respond (OMNR 1997; Riley 1973). As a stand ages, PCT treatment costs increase and growth responses to thinning can decrease (Mann and Lohrey 1974). Therefore, from a forestry perspective, it appears that the best time to conduct PCT in KW plantations would be between ages 10-15; however, this conflicts with conservation goals because the KW occupies stands until 20-25 years. It is unclear if growth response to PCT will be less if thinning is conducted at ages greater than ca. 20 years. As trees age past 20 years in high density plantations their growth may stagnate with lower live crown ratios and may therefore be less responsive to PCT.

In addition to uncertainties regarding timing of PCT in KW jack pine plantations, it is unclear how well jack pine will respond to PCT since the core KW habitat area in northern Lower Michigan consists of the least productive soils, which are extremely xeric and nutrient poor (Gadoth-Goodman and Rothstein 2020). In fact, the Michigan Department of Natural Resources' (MDNR) current silvicultural manual advises that thinning of jack pine stands should only be considered on the highest productivity sites (MDNR 2015b). This aligns with Canadian recommendations that pre-commercial thinning of jack pine should be limited to the best quality sites where one would expect to see a good growth response (OMNR 1997). Alternatively, some management recommendations for Douglas-fir in the Pacific Northwest argue that poor-quality sites have the greatest need for PCT because it could make the difference in merchantability of trees within an economic time frame; whereas stands on high-quality sites can produce a merchantable crop without PCT (Reukema 1975).

I initiated a plot-level thinning experiment to assess growth response to PCT of high-density jack pine plantations planted for KW habitat. The experiment was conducted across two different soil types and three different age classes, to understand how growth response varied with site quality and timing of PCT. In addition, two stands of KW jack pine plantations were put out for commercial bid to assess costs and residual stand characteristics of operational scale PCT. The research questions for this study were:

1. Does jack pine planted at high densities for KW habitat respond to pre-commercial thinning with increased growth?
2. How does growth response vary with stand age at the time of PCT?
3. How does growth response vary between soil types?
4. What are the costs of operational scale implementation of PCT in high-density KW plantations?

2.2 Methods

2.2.1 Plot-Scale Experimental Row Thinning

In spring of 2017, I initiated a plot-scale experiment to assess growth response of KW plantations to pre-commercial row-thinning. I used GIS data provided by the Michigan Department of Natural Resources (MDNR) to identify 18 study locations where high-density jack pine plantations had been established as part of the Kirtland's Warbler recovery program. To assess the influence of stand age on thinning response, I selected six sites each from three distinct age classes. The youngest age class was closest to the theoretically optimal PCT timing during the stand initiation phase, occurring during the later stages of KW occupancy (stands aged: 11, 12, 13, 13, 14 and 14 years). The second age class occurred after the ideal PCT timing, during the self-thinning phase (Gadoth-Goodman and Rothstein 2020) and post KW occupancy (aged: 19, 21, 21, 22, 24 and 26 years). The third age class represented the end of the self-thinning phase (Gadoth-Goodman and Rothstein 2020) and occurred well past the end of KW occupancy (aged: 27, 33, 33, 33, 33 and 35 years).

To assess the influence of soil type on thinning response, half of the stands within each age class were selected on Grayling Sands (Typic Udipsamment) and half selected on Graycalm Sands (Lamellic Udipsamment). These are the two major soil series that support jack pine forests across northern Lower Michigan (Werlein 1998). The soil series for my sites were identified by using Natural Resources Conservation Service soil surveys (NRCS 2019). Both soil series have xeric, sandy profiles developed on outwash plain landforms, but Graycalm sands are distinguished by the presence of clay lamellae that improve water retention and increase forest productivity (McFadden et al. 1994; Werlein 1998). The final design had three replicate stands within each age class x soil type combination. Within each stand, I located three plots which were randomly assigned to one of three treatments: i) control, ii) cut 1 row and leave 2 rows (hereafter referred to as “Cut 1”), and iii) cut 2 rows and leave 4 rows (hereafter referred to as “Cut 2”).

The unusual “opposing-wave” configuration of KW plantations that incorporates regular unplanted gaps for foraging habitat (Figure 2.1), presents challenges for setting up study plots. My first step for plot location was to use aerial imagery to identify locations within a single planting strip, or adjacent planting strips that were as homogenous as possible in terms of tree cover and abundance of deciduous tree species. Within these locations, I identified three starting points for plot setup each at the edge of a foraging gap (Figure 2.1). Each starting point became the corner of a plot that was 12 rows wide (ca. 21 meters) by 16 trees long (ca. 24 meters); treatments were applied to the entire area. Trees in cut rows were felled by hand using chainsaws in April and May of 2017. In the middle of each plot, I located an interior measurement plot of 24 trees, consisting of 4 rows, all of which were 6 trees long. In Control and Cut 2 treatments interior measurement plots were 4 rows wide, whereas in the Cut 1 treatment, measurement areas were 5 rows wide (1 cut row between 4 leave rows).

Figure 2.1. Aerial view of a Kirtland's warbler jack pine plantation with markers indicating the northwest corners of each of three plots. Plot 1 is a control treatment, Plot 2 is a cut 2-leave 4 treatment, and Plot 3 is a cut 1-leave 2 treatment. Imagery is from 2020, three years following application of thinning treatments.

Initial diameter measurements were taken in May and June of 2017. Diameters were recorded to the nearest mm at the nearest point to 1.4 m height where the bole was clear of branches or deformities. Each tree was numbered, and location of the measurement point was marked with permanent paint to ensure remeasurements were always done at the exact same spot on the bole. I revisited the plots and measured diameters again in November of 2019 and October of 2020, after three and four growing seasons, respectively. During 2019 sampling, I used a height pole to measure total height and height of the live crown to the nearest cm of each tree. I calculated live crown ratio (LCR) for each tree as: ((Total Height – Crown Height) / Total Height) * 100. Diameter growth over the course of the experiment was calculated as: 2020 DBH – 2017 DBH. Ideally, I would have included 1,296 trees in my analysis (24 trees * 18 sites * 3 treatments). However, 142 of these trees were dropped because they were already dead at the start of the experiment (primarily from the oldest age class), 23 trees were dropped because they died between 2017 and 2020, and 60 trees were dropped because they had missing data for at least one year. My final data set consisted of 1071 trees.

2.2.2 Stand-Scale Operational Thinning

To understand feasibility and costs associated with applying PCT to post-occupancy KW plantations I worked with MDNR to set up a commercial bidding process for a mechanical, every third row thinning of three stands of 20-25 year-old KW plantations. A commercial operator bid on the project and completed work on one of the three stands (aged 24 years) in the winter of 2020, before budget cuts due to the novel coronavirus pandemic shut down the project. For the completed work, the operator used a masticator to chip all the trees in every third row. Subsequently, MDNR initiated another commercial bidding process for a selective, hand thinning operation in a single 25 year-old stand. Hand thinning was conducted in winter of 2021 by a commercial crew using chainsaws with a cutting guide instructing them to remove ca. every third tree within all rows, with specifications to avoid crop trees and dominant crown condition class trees.

Prior to the start of both mechanical and selective thinning operations, I set up a grid of permanent sampling points at 1 plot per 4 hectares. If the grid placed a plot starting point in a foraging gap, I moved plot center to the nearest point that was 3 planting rows away from the gap edge to ensure I would have trees to measure. Plots were roughly rectangular with dimensions of 8.5 meters in length and a width of 4 planting rows to ensure a minimum of 16 trees (trees planted on a 1.8 m spacing) within each plot. Prior to operations in each stand, I measured initial DBH, assigned a crown condition class, and recorded the row position of each tree in every plot. I relocated each plot post thinning and recorded which trees were cut and which were left. For both pre and post thinning, I calculated basal area (BA) in square meters per hectare, trees per hectare, and quadratic mean diameter (QMD) in centimeters.

2.2.3 Statistical and Financial Analyses

I used a linear mixed-effects model to evaluate the best predictors of individual tree diameter growth and live crown ratio in the plot-level thinning experiment from the factors: stand age, soil series, thinning treatment, and initial DBH. The model was set up with treatment type (plot) nested within stands and stand was treated as a random effect. Response variables for this analysis were individual tree diameter growth from spring 2017 to autumn 2020 and LCR in autumn 2019. Residuals of diameter growth and LCR were both normally distributed. For each response variable, 18 models with various combinations of predictors with additive and/or multiplicative properties were run against each other. I used Akaike's Information Criteria (AIC) to compare my 18 models. Models are considered to have strong empirical support if they are within two AIC units of the minimum AIC (Burnham and Anderson 2002). Four of the models were well supported hence the final model was chosen because it had the majority of the weight. All model fitting was conducted with RStudio version 1.2.5033. For the operationally thinned sites, I completed a chi-square analysis to compare crown condition class distribution between the pre and post-thinning. The null hypothesis stated there was no difference in the distribution of stems among crown condition classes before and after thinning.

To assess the financial viability of operational thinning of KW plantations, I utilized break-even yield analysis as described by Fox (1988) to estimate yield increase due to PCT, above expected yield from an unthinned stand, required to break-even financially. I used data from the MDNR stumpage price report for the year of 2021 (MDNR 2022) to estimate average sold price for jack pine pulpwood across MDNR's Atlanta, Grayling and Roscommon Forest Management Units (core KW breeding range) at $23.74 per cord (MDNR 2022). Expected pulpwood volume for untreated 50-year-old KW jack pine plantations is projected to average 21 cords per hectare (from data in Gadoth-Goodman and Rothstein 2020), which when multiplied by $23.74 per cord equates to an average stumpage price of $496.41 per hectare. I calculated the break-even yield using Eq 6 in Fox (1988) assuming that thinning occurred at stand age 20 with final harvest at stand age 50 and various rates of return ranging from 2% to 5%.

2.3 Results

2.3.1 Plot-Scale Experimental Row Thinning

Kirtland's warbler jack pine responded to PCT with increased diameter growth; however, the response varied among thinning treatments and age classes (Figure 2.2). The best linear mixed-effects model for individual tree diameter growth was: Age * Treatment + X2017dbh + Soil + (1|Treatment:Stand) + (1|Stand). This model included age, treatment, initial diameter and soil as predictors with stand (site) and treatment plots nested within stands as random effects. This model had 38% of the AICc weight and was 0.7 AICc units lower than the second-best model. The predictors by themselves explained ~38% of the variation in DBH growth while the predictors and the random effects explained ~59% of the variation. Age ($p<0.001$), initial diameter ($p<0.001$), and TreatmentCut2 ($p<0.05$) were all significant. The treatment variable had a high correlation with the other variables, with a Generalized Variance Inflated Factor (GVIF) of 135, but since this was my variable of interest in this study, I elected to keep it in the model. There was no apparent influence of soil type on DBH growth rate as soil type was not significant (*p*=0.211) in the best fit model.

Overall, diameter growth response was greater in the Cut 1 compared to the Cut 2 treatment, and increased in the older age classes, with the largest increase in diameter growth from the control in the 30-39 year age class (Figure 2.2). The interaction term between age and treatment was marginally significant (p-value = 0.067). The interaction of stand age by treatment is visualized in Figure 2.3, showing that while there was slower overall diameter growth with age, the difference between treatment and control was generally amplified with increasing age. The overall percentage increases of diameter relative to the control for each age class and each treatment are shown in Table 2.1.

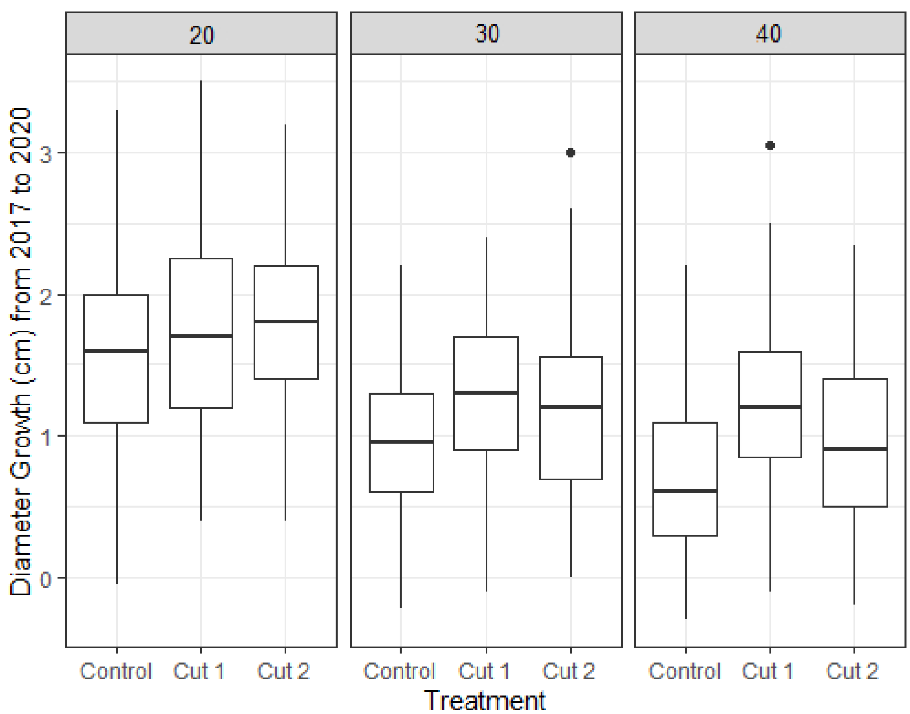

Figure 2.2. DBH growth (cm) of trees in each treatment type organized by 20, 30, and 40 year age classes. The dark lines are medians, the boxes are interquartile ranges, the lines are 95% confidence intervals and the dots are potential outliers.

Table 2.1. Percent increase of treatment from the control separated by age classes. The 40 year age class had the largest increase in diameter growth from the control treatment. The cut 1 treatment had larger increases in the 30 and 40 year age classes than the cut 2 treatment.

Age Class	% Increase of Cut 1 from Control	% Increase of Cut 2 from Control
20	15.75	17.00
30	30.28	21.02
40	55.41	26.98

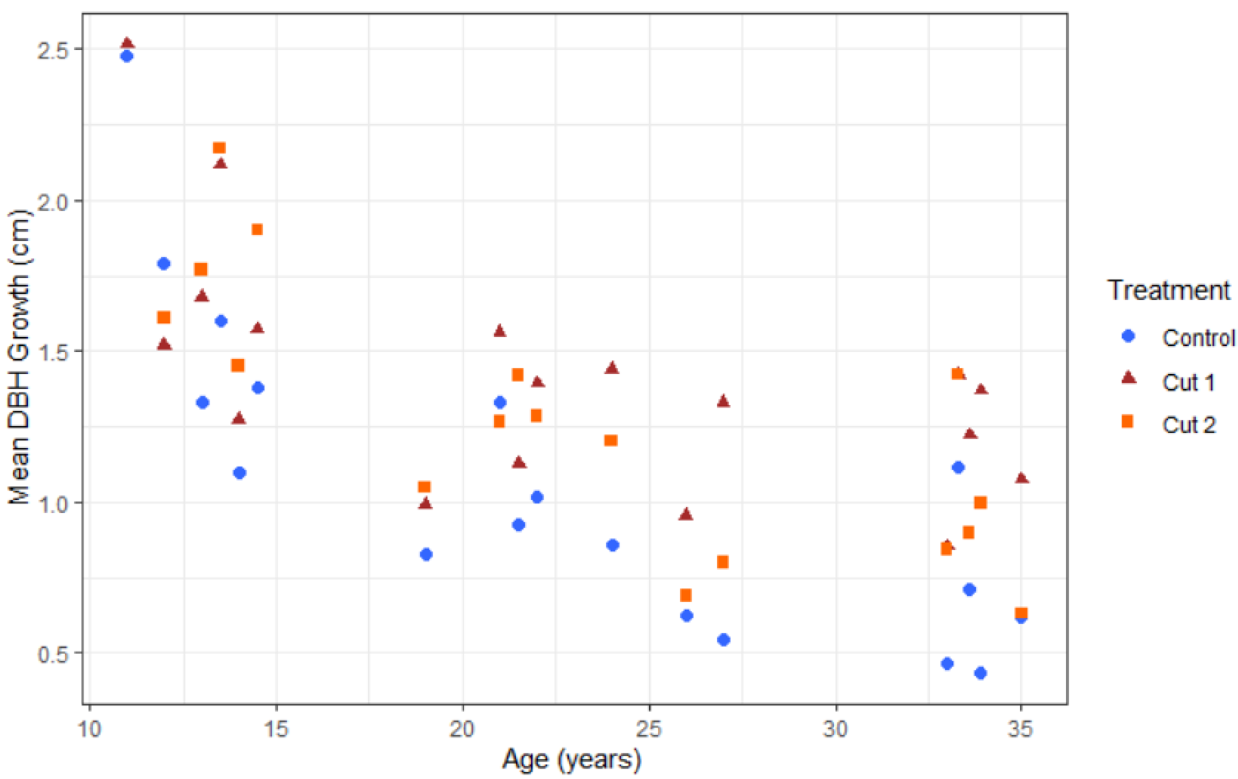

Figure 2.3. Mean DBH growth of trees across treatment types by age.

Live crown ratios declined with increasing stand age; however, PCT appeared to slow this decline with age (Figure 2.4). The best model for live crown ratio was: Age * Treatment + Soil + X2017dbh + (1|Treatment:Stand) + (1|Stand). This model included age, soil, treatment and initial diameter as predictors and with stand (site) and treatment plots nested within stands as random effects. This model had an interaction between age and treatment. This model had 95% of the AICc weight and was 6.8 AICc units lower than the second-best model. The predictors by themselves explained ~54% of the variation in LCR while the predictors and the random effect (stand) explained ~72% of the variation. The p-values were significant ($p < 0.001$) for initial diameter, age, TreatmentCut 2 and Age:TreatmentCut 2 and significant at $p < 0.01$ for TreatmentCut 1 and SoilGrayling. Trees that resided on the Grayling Sands soil series had larger live crown ratios than those on Graycalm Sands soil series, especially in the 20-29 and 30-39 age classes (Figure 2.5). Interaction of stand age by treatment is visualized in Figure 2.6, showing that while LCR decreased with age, the difference between treatment and control was generally amplified with increasing age.

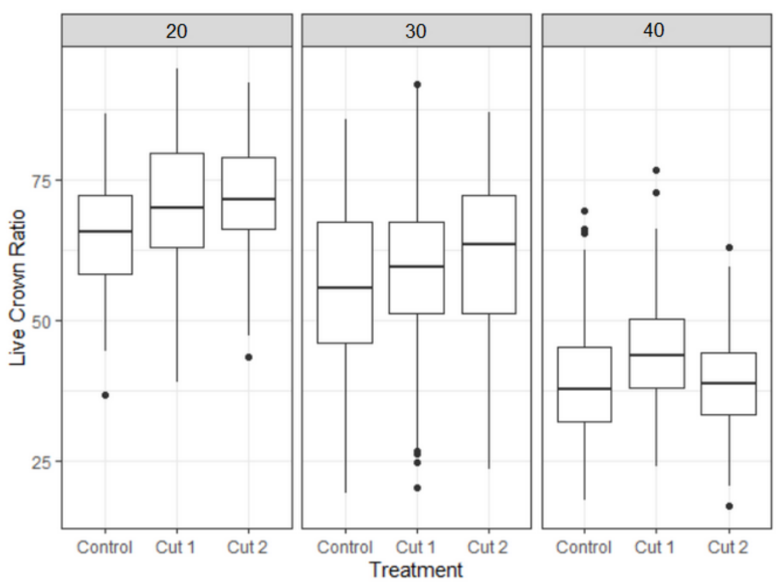

Figure 2.4. Live crown ratio in 2019 of trees by age class (20, 30, 40 years) and treatment type.

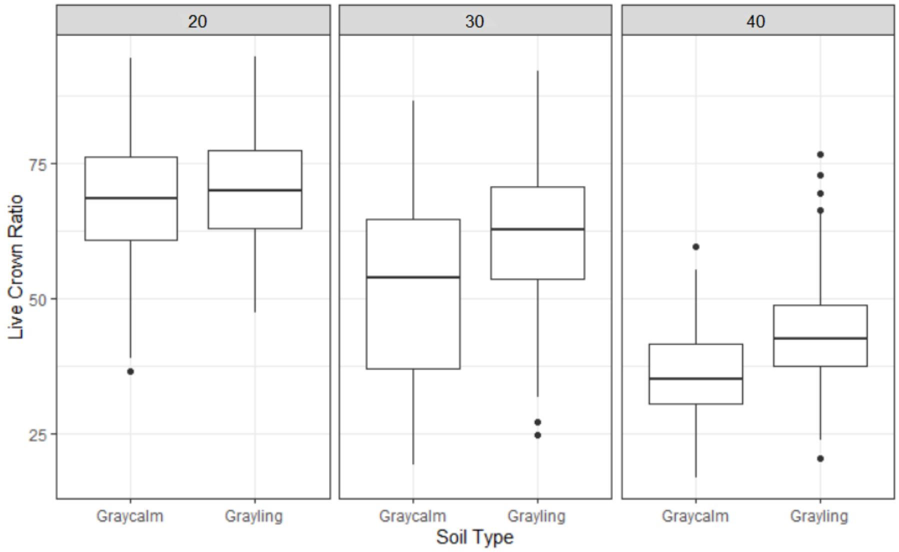

Figure 2.5. Live crown ratio in 2019 of trees by age class (20, 30, 40 years) and soil type.

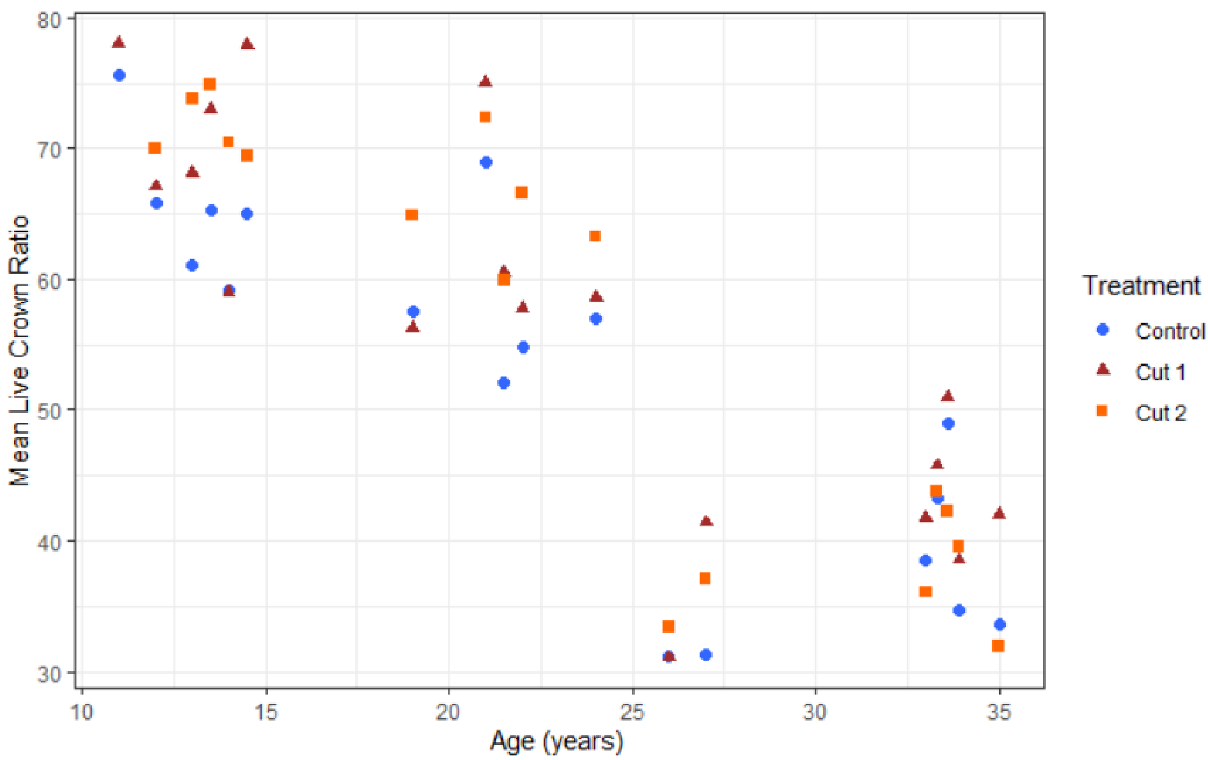

Figure 2.6. Mean live crown ratio of trees across treatment types by age.

2.3.2 Stand-Scale Operational Thinning

The lowest accepted bids for operational PCT came in at $655 per hectare for mechanical row thinning and $912 per hectare for hand thinning. Both mechanical and hand thinning achieved similar decreases in TPH and basal area, whereas hand thinning achieved a slight increase in QMD (Table 2.2). Distributions of stems among crown condition classes before and after thinning treatments are shown in Figure 2.7. As expected, mechanical thinning had no apparent effect on crown condition class distribution (Figure 2.7a; p = 0.950). Hand thinning appeared to decrease the proportion of intermediate and suppressed trees, and increased the proportion of dominant trees; however, these differences were not statistically significant (p = 0.69).

Table 2.2. Summary of pre- and post-treatment stand attributes following operational-scale thinning treatments.

Site (Treatment)	Basal Area (m^2 ha^{-1})	Trees per Hectare	QMD (cm)
Mechanical Thinning			
Pre-Treatment	12.4	3501	6.76
Post-Treatment	10.1	2807	6.83
% Change	*-18.0%*	*-19.8%*	*+1.1%*
Hand Thinning			
Pre-treatment	14.6	3489	7.21
Post-treatment	12.4	2708	7.52
% Change	*-14.9%*	*-22.4%*	*+4.2%*

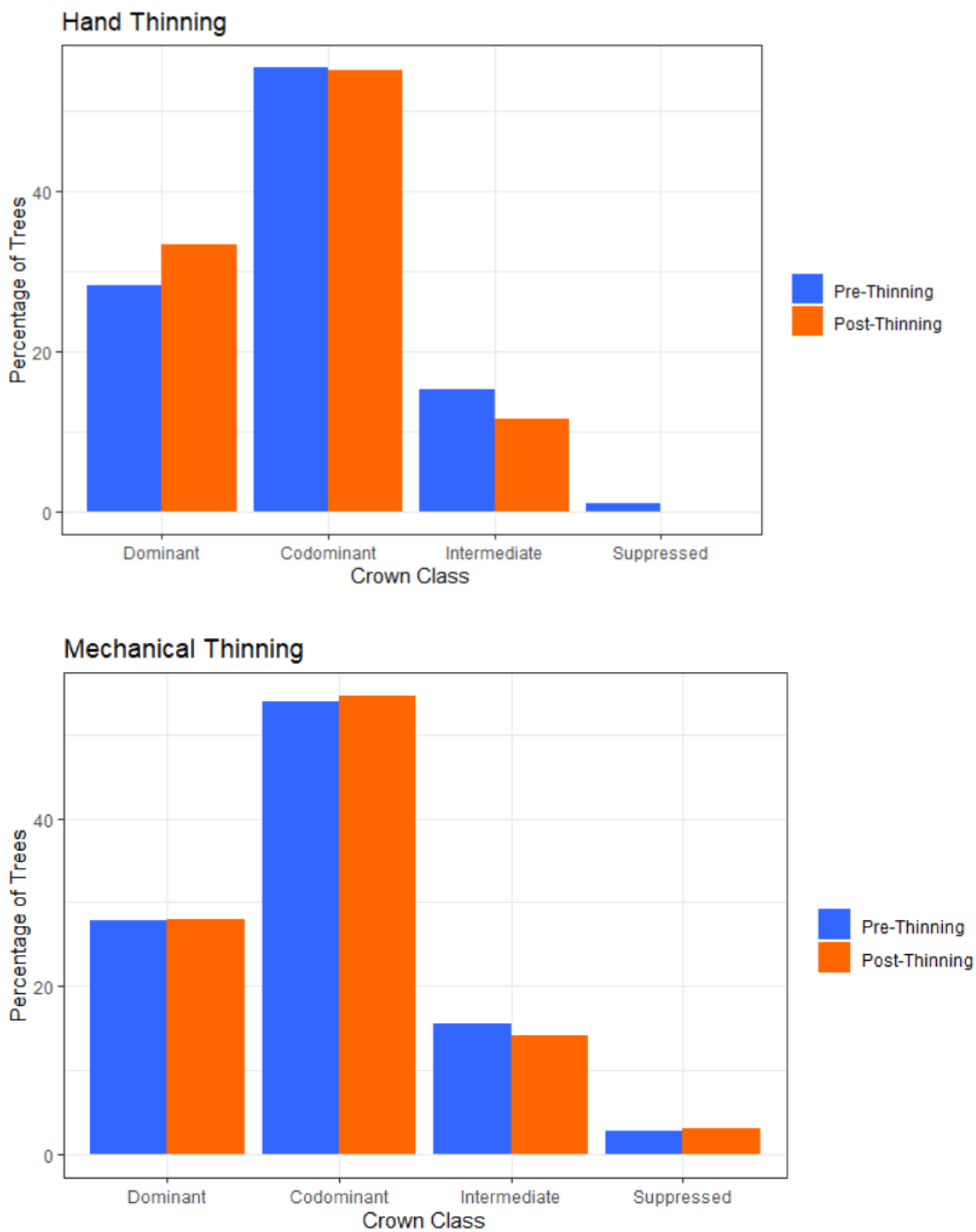

Figure 2.7. Effects of selective vs mechanical thinning on distribution of trees among crown class positions. Data represent the percentage of stems represented in each crown class before treatments, after mechanical row thinning and after selective hand thinning.

Results of my break-even financial analysis of the financial viability of PCT are presented in Table 2.3 below. The stumpage price required to break-even for mechanical thinning ranged from $1187 to $2830 per hectare, depending on the assumed rate of return. This equates to a final harvested volume of 50 to 119 cords per hectare. The stumpage price required to break-even for hand thinning ranged from $1653 to $3941 per hectare, depending on the assumed rate of return. This equates to a final harvested volume of 70 to 166 cords per hectare.

Table 2.3. Stumpage prices and cords per hectare required to break-even with thinning costs at various rates of return.

Rate of Return	Mechanical Thinning Stumpage Price ($ per hectare)	Mechanical Thinning (cords per hectare)	Hand Thinning Stumpage Price ($ per hectare)	Hand Thinning (cords per hectare)
2%	1187	50	1653	70
3%	1588	67	2213	93
4%	2125	90	2958	125
5%	2830	119	3941	166

2.4 Discussion

Overall, I found that pre-commercial thinning of high-density jack pine planted for KW habitat resulted in increased diameter growth, with a greater growth response in the Cut 1 treatment than the Cut 2 treatment. The most likely explanation for this difference is that in the Cut 2 treatment, the two inner rows did not receive any release, only the outer rows received release. The Cut 2 treatment was originally conceived based on conversations with land managers who thought that the local operators' logging equipment might have difficulty removing a single row in these narrowly spaced plantations. However, when later put out operational-scale, third-row thinning for commercial bid, this turned out not to be an issue as the contractor's equipment was able to remove a single row. Since the Cut 2 treatment appears to not be required to accommodate logging equipment, and because the growth response was less than that of the Cut 1 treatment, I conclude that the Cut 2 treatment is not worth pursuing and focus the remainder of my discussion on response of the Cut 1 treatment.

In general, the diameter growth response to PCT from the control increased with increasing stand age (Figure 2.2). Older stands had a larger growth response than younger stands with the greatest growth response in the oldest age class (30-39 years). The oldest age class likely had the greatest growth response because there appears to be stronger aboveground competition in the older stands, whereas in the younger stands aboveground competition appears to be much less, such that removing the smaller trees on these sites had much less of an effect on residual trees. Patterns of LCR with stand age (Figure 2.5) are indicative of above ground competition across the sites. Through the first ca. 25 years of plantation growth, LCRs change very little with stand age and always remain above 0.5 (Figure 2.6). After 25 years, there is a sharp drop in LCR, indicating that increased competition for light results in lifting of the live crowns (Lanner 1985). In contrast, in stands less than 20 years old, trees have not yet fully occupied the site and trees maintain live branches most of the length of the stem. Therefore, it makes sense that removal of competitors in stands 25 years of age and greater would have the greatest impact on growth of the residual trees.

Pre-commercial thinning is recommended during the stand initiation phase because as the stand ages, treatment costs increase and decreased growth responses after thinning can occur (Mann and Lohrey 1974). This timing is also ideal because competition and growth reductions occur well before self-thinning mortality appears (Lindgren and Sullivan 2013). Gadoth-Goodman and Rothstein (2020) found that mortality from self-thinning first appears after age 20 in KW jack pine stands, which suggests the optimal thinning time is well before 20 years of age. Pre-commercial thinning is typically recommended at an early age, with various preferred timings: Mann and Lohrey (1974) recommend PCT for southern U.S. pines species such as loblolly pine within 3-4 years after stand establishment to maintain a rotation length under 35 years, while Reukema (1975) recommends PCT for Douglas-fir in the Pacific Northwest at 10-15 years old, once the trees have expressed their growth and quality characteristics and are less subject to brush competition and animal browsing. It is important to note that jack pine in Michigan has a slower growth rate than southern U.S. pine species hence, the ideal time for PCT on Michigan jack pine would likely be later than recommended for southern pine species.

While older trees (27-35 year old) in this study had a greater short-term growth response, it would still be ideal to conduct PCT on younger trees to reduce the loss of volume on the site and minimize the cost of PCT. Therefore, from a forestry perspective, the ideal time to conduct PCT in KW jack pine plantations would likely be between the ages 10-15, as is recommended for jack pine in nearby Ontario, Canada (Riley 1973; Morris et al. 1994). Trees in the six stands in this age range were all less than 5 meters in height and with a median DBH of 4.8 cm, suggesting that mechanical or hand thinning operations could be relatively inexpensive. However, conducting PCT within this time frame conflicts with conservation goals because the KW occupies stands until they are up to 23 years in age, with peak occupancy in the 12-14 y range (Meyer 2010). Thus, for these plantations, which are planted primarily to provide KW breeding habitat, PCT can likely only be conducted after stands are at least 20 y old. Although PCT of KW jack pine plantations cannot be done as early as would be recommended from a forest production perspective, my data clearly show that deep crowns are still maintained up to stand age 25 and trees are still responsive to release. Therefore, my recommendations for timing would be as soon as possible after KW occupancy ends and before 25 years when LCRs drop rapidly. The KW is a ground-nesting species and builds its nests under low jack pine branches (Mayfield 1960). For this system, the ideal time to conduct PCT would be when the live branches have lifted enough to reduce KW nesting habitat quality, but not so extensively that the trees are not responsive to PCT.

The DBH growth response does not appear to vary between soil types. Soil type had a non-significant p-value of 0.21 in the best fit model for DBH growth. However, trees on the more xeric Grayling Sands soil series had larger live crown ratios than those on Graycalm Sands soil series, especially in the 20-29 and 30-39 age classes. Soil type was not significant in my model for DBH growth, but I decided to keep it in the analyses because it can be ecologically important. In fact, Kashian and Barnes (2000) noted that soil factors affecting moisture regime in sandy soils are a major source of variation in jack pine growth. Even so, there was no clear effect of soil type on DBH growth in my study. The MDNR's current silvicultural manual advises that thinning of jack pine stands should only be considered on the highest productivity sites (MDNR 2015b). This aligns with Canadian recommendations that pre-commercial thinning of jack pine should be limited to the best quality sites where one would expect to see a good growth response (OMNR 1997). On the other hand, some management recommendations for Douglas-fir in the Pacific Northwest argue that poor-quality sites have the greatest need for PCT because it could make the difference in the merchantability of the trees within an economic time frame; whereas stands on high-quality sites can produce a merchantable crop without PCT (Reukema 1975).

Although there was not any clear effect of soil type on DBH growth, my data suggest that jack pine crowns are lifting sooner on more mesic Graycalm Sands soils compared to the more xeric Grayling Sands. This suggests that trees on Graycalm Sands are growing faster and thus the competitive interactions that lead to crown lifting are also happening sooner (Lanner 1985). This effect does not appear in my DBH growth data, but LCR could perhaps be a more sensitive indicator. Since trees on Graycalm Sands soils had smaller live crown ratios, the trees could lose their lower branches and possibly stop supporting KW breeding habitat earlier than trees on Grayling Sands soils. Kashian and Barnes (2000) found that jack pine stands that grew faster due to better microclimate aged out of KW habitat more quickly. If KW occupancy ends earlier on sites with Graycalm Sands soil, it may be possible to conduct PCT earlier which may result in increased DBH growth.

While my results for DBH growth were collected only after a few years of PCT, I believe it is unlikely for increased future volume growth to ever recoup the costs of PCT. Under my most optimistic scenario (2% rate of return) PCT would need to increase final harvest volume by 139% for mechanical thinning and 233% for hand thinning. Under the most pessimistic assumed rate of return (5%) PCT would need to increase final harvest volume by 470% for mechanical thinning and 694% for hand thinning. Recall that on average I observed only a 16% to 55% increase in diameter growth in my Cut 1 treatment depending on the respective age classes: 20, 30 and 40. Furthermore, the final harvest volumes required to break-even (50-119 cords per hectare; Table 2.3), appear to be impossibly high for this forest type. In an unpublished review of harvest volumes from mature jack pine stands, MDNR found they ranged from 15-40 cords per hectare (median = 22; J. Hartman, MDNR personal communication). Therefore, I conclude that PCT does not appear to be financially feasible at any rate of return (Table 2.3).

The low value of jack pine is likely the major constraint in this system; however, since KW plantations are on public land managed by state and federal agencies, the financial bottom line does not drive all decision making. It is only one of many factors for forest managers to consider. For example, another consideration is the fact that legacies of past management on the current stand age distribution (Tucker et al. 2016) has resulted in a situation where a lack of mature jack pine will constrain agency efforts to regenerate new KW habitat over the coming decades. Even though PCT of KW plantations may never break-even financially, the practice may be warranted on public lands if it can accelerate diameter growth in order to move current KW plantations to marketable size trees more quickly. Another non-financial consideration that could motivate public land managers to consider PCT in high-density jack pine plantations is improved resilience to climate change. Jack pine populations that provide the bulk of KW breeding habitat occur at the very southern limit of the tree species' distribution and have long been recognized as uniquely vulnerable to a warming climate (Botkin et al. 1991; Donner et al. 2018). Thinning is also a silvicultural tool that can be used to increase resilience and resistance to drought by increasing water availability to residual trees (D'Amato et al. 2013; Giuggiola et al. 2013). Jack pine is at the southern limit of its range, threatened by a warming climate, and density reduction is an important silvicultural tool to try to make stands more resilient to climatic warming.

2.5 Conclusions

Despite the cost of PCT, it remains a suitable option to maintain the commercial bidding of KW plantations. For land managers, the risk of no commercial bids on KW plantations may be greater than the cost of PCT. Kirtland's Warbler Management Areas are managed on a rotating schedule with older jack pine being harvested and jack pine seedlings being planted on the same site. These KW jack pine harvests are executed by commercial bidders who bid on available timber sales. There is concern that commercial bidders may not want to bid on a timber sale with small diameter jack pine if they do not find the harvest profitable, forcing public land managers to find another option to clear the site and prepare it for planting. This presents an issue since state and federal agencies are contractually obligated to plant jack pine every year to provide continual KW habitat and older KW plantations must be cleared to provide available land for planting jack pine. If PCT is conducted it will ensure the stand has larger diameter jack pine than untreated stands at final harvest and may prove more profitable and desirable to bidders, ensuring the continuous commercial bidding of KW plantations. Another benefit to PCT, is that it can be used to increase resilience to drought by increasing water availability to residual trees, reducing stress and increasing tree vigor (D'Amato et al. 2013; Giuggiola et al. 2013). Jack pine is at the southern limit of its range, threatened by a warming climate, and density reduction is a potential silvicultural tool to attempt to make stands more resilient to climatic warming. Even though PCT of KW plantations may never break-even financially, the practice may be justified on public lands if it can accelerate attainment of marketability and maintain the current commercial bidding system while increasing resilience to climatic warming by reducing stress and increasing tree vigor.

REFERENCES

Bella, I. E., & DeFranceschi, J. P. (1980). Spacing effects 15 years after planting three conifers in Manitoba. Environment Canada, Canadian Forestry Service, Northern Forest Research Centre, Edmonton, Alberta. (NOR-X-223).

Benzie, J. W. (1977). Jack pine in the north central states (Vol. 32). North Central Forest Experiment Station, United States Department of Agriculture, Forest Service.

Bocetti, C. I., Goble, D. D., & Scott, J. M. (2012). Using conservation management agreements to secure postrecovery perpetuation of conservation-reliant species: The Kirtland's warbler as a case study. BioScience, 62(10), 874-879.

Botkin, D. B., Woodby, D. A., & Nisbet, R. A. (1991). Kirtland's warbler habitats: a possible early indicator of climatic warming. Biological Conservation, 56(1), 63-78.

Burnham, K. P., & Anderson, D. R. (2002). A practical information-theoretic approach. Model selection and multimodel inference, 2, 70-71.

Byelich, J., DeCapita, M. E., Irvine, G. W., Radtke, R. E., Johnson, N. I., Jones, W. R., Mayfield, H., & Mahalak, W. J. (1976, revised 1985) Kirtland's Warbler recovery plan. United States Fish and Wildlife Service.

Cleland, D. T., Crow, T. R., Saunders, S. C., Dickmann, D. I., Maclean, A. L., Jordan, J. K., Watson, R. L., Sloan, A. M., & Brosofske, K. D. (2004). Characterizing historical and modern fire regimes in Michigan (USA): A landscape ecosystem approach. Landscape Ecology, 19(3), 311-325.

D'Amato, A. W., Bradford, J. B., Fraver, S., & Palik, B. J. (2013). Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. Ecological Applications, 23(8), 1735-1742.

Donner, D. M., Brown, D. J., Ribic, C. A., Nelson, M., & Greco, T. (2018). Managing forest habitat for conservation-reliant species in a changing climate: The case of the endangered Kirtland’s Warbler. Forest Ecology and Management, 430, 265-279.

Fox, B. (1988). Estimating returns on forest investments using break-even yield analysis. Southern Journal of Applied Forestry, 12(4), 264-266.

Gadoth-Goodman, D., & Rothstein, D. E. (2020). Alternative Silvicultural Approaches to Managing Jack Pine Plantations for Endangered Species Habitat and Forest Products. Forest Science, 66(2), 210-220.

Giuggiola, A., Bugmann, H., Zingg, A., Dobbertin, M., & Rigling, A. (2013). Reduction of stand density increases drought resistance in xeric Scots pine forests. Forest Ecology and Management, 310, 827-835.

Godman R. M., & Cooley, J. H. (1970). Effect of initial spacing on Jack Pine growth and yield. Michigan Academician, 2(4), 107-111.

Guilkey, P. C., & Westing, A. H. (1956). Effects of initial spacing on the development of young jack pine in northern Lower Michigan. Papers of the Michigan Academy of Science, Arts and Letters, 41, 45-50.

Janas, P. S., & Brand, D. G. (1988). Comparative growth and development of planted and natural stands of jack pine. The Forestry Chronicle, 64(4), 320-328.

Kashian, D. M., & Barnes, B. V. (2000). Landscape influence on the spatial and temporal distribution of the Kirtland's warbler at the Bald Hill burn, northern Lower Michigan, USA. Canadian Journal of Forest Research, 30(12), 1895-1904.

Kepler, C. B., Irvine, G. W., DeCapita, M. E., & Weinrich, J. (1996). The conservation management of Kirtland's Warbler *Dendroica kirtlandii*. Bird Conservation International, 6(1), 11-22.

Lanner, R. M. (1985). On the insensitivity of height growth to spacing. Forest Ecology and Management, 13(3-4), 143-148.

Lindgren, P. M. F., & Sullivan, T. P. (2013). Long-term responses of tree and stand growth of young lodgepole pine to pre-commercial thinning and repeated fertilization. Forest Ecology and Management, 307, 155-164.

Mann, W. F., & Lohrey, R. E. (1974). Pre-commercial thinning of southern pines. Journal of Forestry, 72(9), 557-560.

Mayfield, H. (1953). A census of the Kirtland's Warbler. The Auk, 70(1), 17-20.

Mayfield, H. F. (1960). The Kirtland's warbler (No. 40). Cranbrook Institute of Science.

Mayfield, H. (1962). 1961 decennial census of the Kirtland's warbler. The Auk, 79(2), 173-182.

Mayfield, H. F. (1972). Third decennial census of Kirtland's Warbler. The Auk, 89(2), 263-268.

McFadden, J. P., MacDonald, N. W., Witter, J. A., & Zak, D. R. (1994). Fine-textured soil bands and oak forest productivity in northwestern lower Michigan, USA. Canadian Journal of Forest Research, 24(5), 928-933.

MDNR. (2015a). Kirtland’s Warbler breeding range conservation plan. Michigan Department of Natural Resources. https://www.michigan.gov/documents/dnr/Kirtlands_Warbler_CP_457727_7.pdf

MDNR. (2015b). Silvics and management guidance manual. Michigan Department of Natural Resources. https://www.michigan.gov/documents/dnr/Silvics_guide_493803_7.pdf

MDNR. (2022). 2021 Stumpage Price Report. Michigan Department of Natural Resources. https://www2.dnr.state.mi.us/ftp/forestry/tsreports/StumpagePriceReports/12 Month Stumpage Price Reports/2022 Stumpage Price Reports, 12 Months

Meyer, R. (2010). Dendroica kirtlandii. Fire Effects Information System, [Online]. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, FireSciences Laboratory.

Morris, D. M., Hills, S. C., & Bowling, C. (1994). Growth and form responses to pre-commercial thinning regimes in aerially seeded jack pine stands: 5th year results. The Forestry Chronicle, 70(6), 780-787.

Nelson, M. D. (1992). Predicting Kirtland's warbler (*Dendroica kirtlandii*) habitat suitability on the breeding grounds, northern Lower Michigan. Doctoral dissertation, University of Minnesota.

NRCS. (2019). Web Soil Survey. United States Department of Agriculture, Natural Resources Conservation Service. https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

Nyland, R. D., Kenefic, L. S., Bohn, K. K., & Stout, S. L. (2016). Silviculture: Concepts and applications. Waveland Press, Inc.

OMNR. (1997). Silvicultural guide to managing for black spruce, jack pine and aspen on boreal forest ecosites in Ontario. Ontario Ministry of Natural Resources.

Probst, J. R. (1988). Kirtland’s warbler breeding biology and habitat management. Integrating Forest Management for Wildlife and Fish, 28-35.

Reukema, D. L. (1975). Guidelines for precommercial thinning of Douglas-fir (Vol. 30). Pacific Northwest Research Station, United States Department of Agriculture, Forest Service.

Riley, L. F. (1973). Operational trials of techniques to improve jack pine spacing. Great Lakes Forest Research Centre, Canadian Forestry Service, Department of the Environment.

Tong, Q. J., & Zhang, S. Y. (2005). Impact of initial spacing and precommercial thinning on jack pine tree growth and stem quality. The Forestry Chronicle, 81(3), 418-428.

Tong, Q. J., Zhang, S. Y., & Thompson, M. (2005). Evaluation of growth response, stand value and financial return for pre-commercially thinned jack pine stands in Northwestern Ontario. Forest Ecology and Management, 209(3), 225-235.

Tucker, M. M., Corace, R. G., Cleland, D. T., & Kashian, D. M. (2016). Long-term effects of managing for an endangered songbird on the heterogeneity of a fire-prone landscape. Landscape Ecology, 31(10), 2445-2458.

USFWS. (2019). Partners Celebrate Successful Recovery of Beloved Songbird. United States Fish and Wildlife Service. https://www.fws.gov/Midwest/endangered/birds/Kirtland/Kirtland's Warbler Press Release - FINAL with logos.pdf

Werlein, J. O. (1998). Soil Survey of Crawford County, Michigan. United States Department of Agriculture, Natural Resources Conservation Service and Forest Service.

Zhang, S. Y., Chauret, G., Swift, D. E., & Duchesne, I. (2006). Effects of precommercial thinning on tree growth and lumber quality in a jack pine stand in New Brunswick, Canada. Canadian Journal of Forest Research, 36(4), 945-952.

APPENDIX

Table 2.4. Parameter estimates and standard errors of linear mixed-effects models for individual tree diameter growth and live crown ratio. Age:Treatment represents the interaction between age and treatment parameters.

	Parameter Estimate	Standard Error
Diameter Growth Model		
Age	-9.46e-02	1.09e-02
TreatmentCut 1	-7.22e-03	1.81e-01
TreatmentCut 2	4.31e-01	1.91e-01
2017DBH	1.25e-01	8.14e-03
Soil	2.08e-01	1.60e-01
Age:TreatmentCut 1	1.14e-02	6.71e-03
Age:TreatmentCut 2	-6.16e-03	6.90e-03
Live Crown Ratio Model		
Age	-1.79	0.23
TreatmentCut 1	7.06	3.48
TreatmentCut 2	18.46	3.68
2017DBH	1.21	0.15
Soil	6.39	3.48
Age:TreatmentCut 1	-0.12	0.13
Age:TreatmentCut 2	-0.52	0.13