Summer 8-16-2015

Forest Harvesting Productivity and Cost in Maine: New Tools and Processes

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FOREST HARVESTING PRODUCTIVITY AND COST IN MAINE:

NEW TOOLS AND PROCESSES

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A DISSERTATION

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

(in Forest Resources)

The Graduate School

The University of Maine

August 2015

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FOREST HARVESTING PRODUCTIVITY AND COST IN MAINE:

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Dissertation Advisor: Dr. Jeffrey G. Benjamin

An Abstract of the Dissertation Presented
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Computer simulations have been used in forestry and forest operations since around 1960. In many cases such simulations can be used to answer questions that would be time consuming and expensive to investigate in a real-life environment. This dissertation focuses on the use of computer simulation in forest operations to answer questions regarding the profitability of technological advancements, investments in precommercial thinning (PCT), and the use of different harvesting systems. To explore the benefits of decoupling a harvesting system, a new simulation method, called agent based modeling was used. Agent based modeling is primarily used in social sciences but now is increasingly used in other fields due to its flexibility in assigning behavior rules to individual object (agents). Other computer simulations in this study were based on growth & yield models and harvest time simulations.

Results clearly showed that technological advancements in a grapple skidder and stroke delimber system marginally increased profits, whereas the use of two grapple skidders proved to be most profitable in the majority of scenarios tested. Further, results showed that the same profit per unit can be achieved at the first commercial thinning,

whether a stand was previously precommercially thinned or not. Thus, there is no financial gain or loss in investing in PCT at the first thinning, although there will be a faster supply of sawlogs in the future. The last simulation clearly showed that delaying a commercial thinning does not result in a change of maximum net present value (NPV), however, it does change the time in which this NPV can be achieved. The simulation further showed that a cut-to-length harvesting system is the most profitable one in the final harvest of softwood stands in northern Maine.

Overall, these simulations have provided data that in most cases would otherwise not have been possible to collect for years to come. In the future each individual study can be expanded to refine the questions asked or to include an increasing variety of harvesting equipment.

ACKNOWLEDGEMENTS

First of all I would like to thank my advisor Dr. Jeffrey G. Benjamin for taking me on as a Ph.D. student and guiding me through the ups and downs of life in academia. Getting this far would not have been possible without an exceptionally supportive committee. So I want to take this opportunity to thank Drs. Mindy Crandall, Aaron Weiskittel, Timothy Waring, and René Germain for their help and guidance.

Being a Ph.D. student is time consuming and can be frustrating at times. I would like to thank my wife, Emily, for her support and patience with me over the past few years. Without her strength I would not be writing this document today. My family played an important role in succeeding in this program through moral support even though the Atlantic is dividing the two continents we live on. Thanks to my parents and my sister.

As any researcher knows, one rarely works completely alone. During my time as a Ph.D. student I worked closely with faculty and other graduate students on various projects. I would like to thank all of them for helping me advance in this field. Special thanks are due to Drs. Robert Wagner and Brian Roth for their support in formulating research questions as well as their guiding words. I cannot forget to mention the many coffee breaks I shared with Joe Hutton while we both studied under Dr. Benjamin. Thanks to you for listening and providing feedback on all kinds of matters. Lastly I have to thank all the logging companies, equipment operators, and land managers that I have worked with and gotten valuable information from. A lot of the data in my research came from the Cooperative Forestry Research Unit and I would like to thank them for providing data but also allowing me to join their meetings and fall field tours.

Often funding is the limiting factor for researchers. In my case I am happy to thank the School of Forest Resources for supporting my time as a graduate student with a research assistantship. But I also want to acknowledge all the other funding sources that played a vital part in finishing this dissertation. Beside the Cooperative Forestry Research Unit and Maine Agricultural and Forest Experiment Station funding was provided by the FarmBio3 project ("Distributed On-Farm Bioenergy, Biofuels and Biochemicals (FarmBio3) Development and Production via Integrated Catalytic Thermolysis", NIFA Award No. 2012-10008-20271, ARS Project No. 1935-41000-082-15A, ARS-UMaine Cooperative Agreement No. 59-1935-3-003) and the Northeastern States Research Cooperative through funding made available by the USDA Forest Service.

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PROLOGUE

The forest resources industry is one of the most important businesses in Maine. Approximately 82% of Maine's land area is forested (McCaskill et al. 2011), which makes it, by percentage of forest cover, one of the most forested states in the nation. Total revenue from Maine's forest in 2005 was $6.47 billion or $916.58 per forested hectare (NESFA 2007). The forest resources industry, and in particular the logging industry, are not without challenges. More than 60% of the logging business owners in Maine are over fifty years of age and the average business owner age is in the low fifties (Leon and Benjamin 2013). Informal and private discussions with several logging contractors in 2013 and 2014 showed that recruiting their own children to take over the logging business proves to be difficult, mostly due to the odd working hours and the comparatively small compensation for it. Some logging business owners even suggest that their own children do not start a logging business.

Another challenge is that harvesting equipment is very capital intensive and the cost of a single machine ranges from approximately $300,000 to $600,000 (Rankin 2015). Other challenges include the uncertainty of the volume of timber that can be contracted in the near future. Often land managers are not willing or able to supply a logging contractor with a timber supply contract for an extended period of time, such as the four to five years of equipment financing period (personal communication with logging contractors). This uncertainty of timber to cut makes it difficult for logging contractors to invest in new equipment. But there are also challenges that are out of the control of a logging contractor or land manager. Leon and Benjamin (2013) reported that weather conditions are the number one factor influencing productivity, followed by market price, and mechanical breakdowns.

Road conditions are also a factor that influence productivity (Leon and Benjamin 2013) but are often out of the hand of logging contractors and sometimes even out of the hand of land managers. In recent years, several mills in Maine closed which presents a new challenge to the forest industry. The closure of mills causes an increase in the transportation distance of wood products to the buyer, and subsequently causes an increase in transportation costs. Leon and Benjamin (2013) further reported other factors that influence the productivity of a logging business which are of lesser concern.

With this in mind it is therefore important to effectively and efficiently manage and operate harvesting equipment. In many cases, innovation plays a vital role in achieving such goals, however, innovation can be costly and it is not guaranteed that an investment in innovation bears any returns (Stone et al. 2011). Rather than doing costly and time consuming experiments to ascertain the outcomes of innovations, it may be more appropriate to simulate the outcome of investments in innovative technology. The use of computer simulation models is often warranted as simulations are less expensive and faster than actual field trials (Winsauer and Underwood 1980; Bradley et al. 1976; Newnham 1968). Computer simulations have long been used to answer forest harvesting questions and to investigate the relationship between system configurations and the operating environment (Baumgras et al. 1993; Winsauer and Underwood 1980; Goulet et al. 1980b; Goulet et al. 1979; Bradley et al. 1976; Newnham 1968). Often the simulation of costs is of further importance. Contreras and Chung (2011), for example, were interested in the costs of thinning operations, while Abbas et al. (2013) modeled and analyzed supply chain cost of forest biomass. Both studies show the importance of simulations in the analysis of costs in the forest industry. In addition, forest succession and management are also common topics for simulations (e.g. Ranatunga et al. 2008; Shifley et al. 2006).

Improving forest operations in Maine can happen at two levels: (1) a technical improvement on the machine level, and (2) a change in system configuration by using alternative equipment. A technical improvement, for example, could be the use of new technology such as Geographic Information Systems (GIS) and Global Position Systems (GPS). A change in system configuration could be the use of a smaller machine or a change from a whole-tree harvesting system to a cut-to-length harvesting system in the same stand. According to Stone et al. (2011) these types of improvement can be seen as a form of process innovation. Being innovative in the logging business has been shown to lessen a company's aversion to financial risk and increased its motivation to invest in new equipment (Allen et al. 2008). This means, that the results of our simulations might encourage logging businesses to invest in innovative tools and technology, which could potentially strengthen their business.

The objective of this study was to use computer simulation methods to evaluate the effect of such technical improvements and changes in system configuration on its profitability. This dissertation consists of four chapters and a concluding Epilogue. Chapters 1 and 2 describe a technical improvement, where the use of GIS and GPS information within grapple skidders and stroke delimbers to decrease machine idle time and unit cost of production is simulated. In addition, the effect of decreasing stroke delimber processing time per tree by one second and the use of two grapple skidders is evaluated as well. Chapter 1 describes the complete model in its detail, while Chapter 2 applies the model to a case scenario and analyses its results.

Chapters 3 and 4 describe the effect of a change in harvesting system configuration. Chapter 3 focuses on the productivity and costs of a cut-to-length (CTL) and whole-tree (WT) harvesting system operating in treatment units with and without earlier precommercial thinning treatments, respectively. Chapter 4 investigates the optimal economic rotation time of six spruce/fir stands using three different harvesting systems and six different treatments. In addition to the CTL and WT harvesting system this chapter also simulates the use of a hybrid system consisting of a feller-buncher, processor, and forwarder.

CHAPTER ONE:

THE EFFECT OF STAND HARDWOOD COMPONENT ON GRAPPLE SKIDDER AND STROKE DELIMBER IDLE TIME AND PRODUCTIVITY – AN AGENT BASED MODEL

ABSTRACT

The forest industry is a capital intensive business and therefore high efficiency in management and forest operations is a must. Maine has millions of acres of forest stands with tree diameters smaller than 30 cm. The harvest productivity in such stands is low compared to stands with larger diameter trees. A recent harvest productivity study in Maine identified operational constraints for whole tree harvest systems, but efforts to improve active harvest operations by implementing experimental system configurations would be expensive and time consuming. A common practice to reduce costs and time consumption of research projects is to develop simulation models and implement new ideas within them. We developed a production efficiency model that leverages an agent-based modeling approach to investigate the effectiveness of different experimental equipment configurations and technical improvements within the communication of harvesting equipment. The model is based on the interaction of two common forest machines (grapple skidder and stroke delimber) and incorporates empirical cycle time estimates from research in Maine. Four scenarios have been developed to investigate baseline conditions, two GPS/GIS improvements, and the use of two grapple skidders.

The goal of this paper is to document a new agent based model that investigates the effectiveness of experimental harvesting system changes and to investigate the effect of hardwood component on machine idle time and productivity. Results showed that system productivity was affected by skidding distance, bunch spacing, and removal intensity. An increase in hardwood component led to a decrease in stroke delimber idle time but did not affect grapple skidder idle. Further, hardwood component did not affect system productivity, and none of the three single-skidder scenarios tested performed any better than another. We verified the model by conducting a sensitivity analysis to confirm previous research results. Data used to verify the model was from the same harvest sites that were used to develop the cycle time equations used in this model. The modeled waiting times are well within the range of observed values and therefore suggest that this model is accurate and well calibrated. Our conclusions are that when operating under average harvesting conditions there is no loss in productivity due to a change in hardwood component and that a stroke delimber idle time of 40% or more is unavoidable unless the stroke delimber can work independently. Future applications of this model may target specific production forestry conditions. Suggested analyses include productivity gains from technological improvements as well as the unit cost of production under a variety of stand and site conditions.

INTRODUCTION

Due in part to regenerating clearcuts from the spruce budworm era in the 1970s and 1980s, forest operations managers in Maine must currently manage an increasing percentage of stands that consist of small-diameter stems (dbh <30 cm). Approximately 11 million acres of forest land in Maine contain or are dominated by trees smaller than 30 cm in dbh (McCaskill et al. 2011). Forest operations are an important part of the forest industry but are also very capital intensive (Purfürst 2010). Due to the high capital investment in harvesting equipment, and the cost of running the machines, it is important to know machine productivity to fully utilize the individual machines. Effective management of forest operations therefore requires accurate estimates of harvest costs and productivity, although the monitoring of these variables may be difficult (Holzleitner et al. 2011; Wang et al. 2004), especially in small diameter stands with an increased number of stems. The two dominant and fully mechanized harvesting systems in Maine are whole-tree (feller-buncher, grapple skidder, stroke delimber) and cut-to-length (harvester, forwarder) (Leon and Benjamin 2013). As the names suggest, whole-tree harvesting operations severe the tree from the stump and then transport it to the roadside including all branches as a whole tree. Cut-to-length harvesting operations severe trees from the stump and then cut off the branches and crosscut the bole into specific length logs, which are then transported to the roadside. These harvesting systems are generally very productive when operating in large diameter tree stands but have a reduced productivity when operating in small diameter tree stands (Hiesl and Benjamin 2013b). With high investments in equipment it is therefore crucial to achieve high machine productivities to keep the unit cost at a low level. To increase the productivity of individual machines and the harvesting system it is therefore necessary to improve or change existing harvesting processes.

The primary goal of any logging contractor is to generate revenue to pay for the equipment and to create income. Maximizing machine utilization is one way to reach this goal (Bolding 2008), but often a contractors focus is more on increasing throughput and productivity, with a minor focus on overall machine utilization. Increasing throughput and productivity will increase revenue and create more income, but to truly maximize the productive potential of each machine, it is necessary to work with a high machine utilization. In order to maximize the utilization of a machine it is important to know where bottlenecks are.

Several methods are available to identify these bottlenecks. Time studies are a common tool to evaluate harvesting operations and identify bottlenecks, however, they can be rather time consuming (Bazghandi 2012; Bolding 2008; Bradley et al. 1976). Another accepted method to analyze the productivity and impact of a harvesting system are simulation models (Li et al. 2006; Wang and LeDoux 2003; Baumgras et al. 1993; Polley 1987; Goulet et al. 1979; Garner 1978; Bradley et al. 1976). Also often used are individual tree growth simulators such as Forest Vegetation Simulator (FVS) (Dixon 2002), and regional volume and taper equations (e.g. Li et al. 2012; Weiskittel and Li 2012). Individual tree growth models are especially useful in combination with cycle time equations for harvesting equipment that are based on individual trees (e.g. Hiesl and Benjamin 2015; Hiesl and Benjamin 2013a; Spinelli et al. 2010; Adebayo et al. 2007). Simulation models have several benefits compared to time and motion studies, such as fast execution of models and the possibility of changing system settings without changing the real system (Bazghandi 2012; Polley 1987; Bradley et al. 1976). The use of simulation models is not new to the forestry community as simulation models have been available since the 1960's (Polley 1987; Goulet et al. 1979).

Before 2013, no harvesting productivity studies were conducted in Maine and therefore no up-to-date productivity information for harvesting systems operating in Maine's forests was available to conduct such computer simulations (Hiesl and Benjamin 2013b). In 2012 and 2013, researchers at the University of Maine collected cycle time and productivity data for five pieces of equipment (feller-buncher, harvester, grapple skidder, forwarder, stroke delimber) commonly used in Maine, and developed cycle time and productivity equations (Hiesl and Benjamin 2015a; Hiesl 2013; Hiesl and Benjamin 2013a; Hiesl and Benjamin 2013c). With these newly developed equations it is now possible to simulate the time consumption and productivity of different harvesting systems in a variety of site and stand conditions. The logical extension of the time and motion study conducted by Hiesl (2013) therefore is to use this data to identify bottlenecks and to develop simulations with the new productivity data to test various scenarios of possible improvements in forest operations. Observations during the field study showed that harvesting operations consist of a large amount of non-productive waiting time that costs the logging business owner money but does not return any valuable product.

Harvesting equipment used in whole-tree and cut-to-length harvesting systems, respectively, mostly operate independent from each other. The interactions between stroke delimbers (Figure 1.1) and grapple skidders (Figure 1.2) are an exception to this. The grapple skidder delivers wood to be processed by the stroke delimber and often has to wait for the stroke delimber to finish processing wood from the previous load. Polley (1987) found that waiting times between 20% and 40% of productive machine hours have to be expected due to this dependency. The recommendation from Polley's research was to avoid such technological coupling of new equipment. Today, however, these two machines are still very much dependent on each other. Huth et al. (2004) commented that the existence of harvesting systems for many years and decades does not necessarily mean that their use is sustainable. Today with decreasing profit margins (Timber Harvesting 2011), large percentages of idle time due to technical coupling of grapple skidder and stroke delimber cannot be tolerated.

Whole-tree harvesting systems are the most important harvesting systems in Maine in terms of volume cut (Leon and Benjamin 2013). Unpublished data of Hiesl (2013) showed that there is a waiting time ranging from 0% to 57% observed when a grapple skidder and stroke delimber work together at a variety of commonly encountered site and stand conditions in Maine (Figure 1.3).

Figure 1.1: A grapple skidder generally transports several trees in a bunch from the forest to the roadside where the whole trees get processed by a stroke delimber.

Figure 1.2: A stroke delimber generally processes one tree at a time by cutting of branches and the top above a specific merchantable diameter.

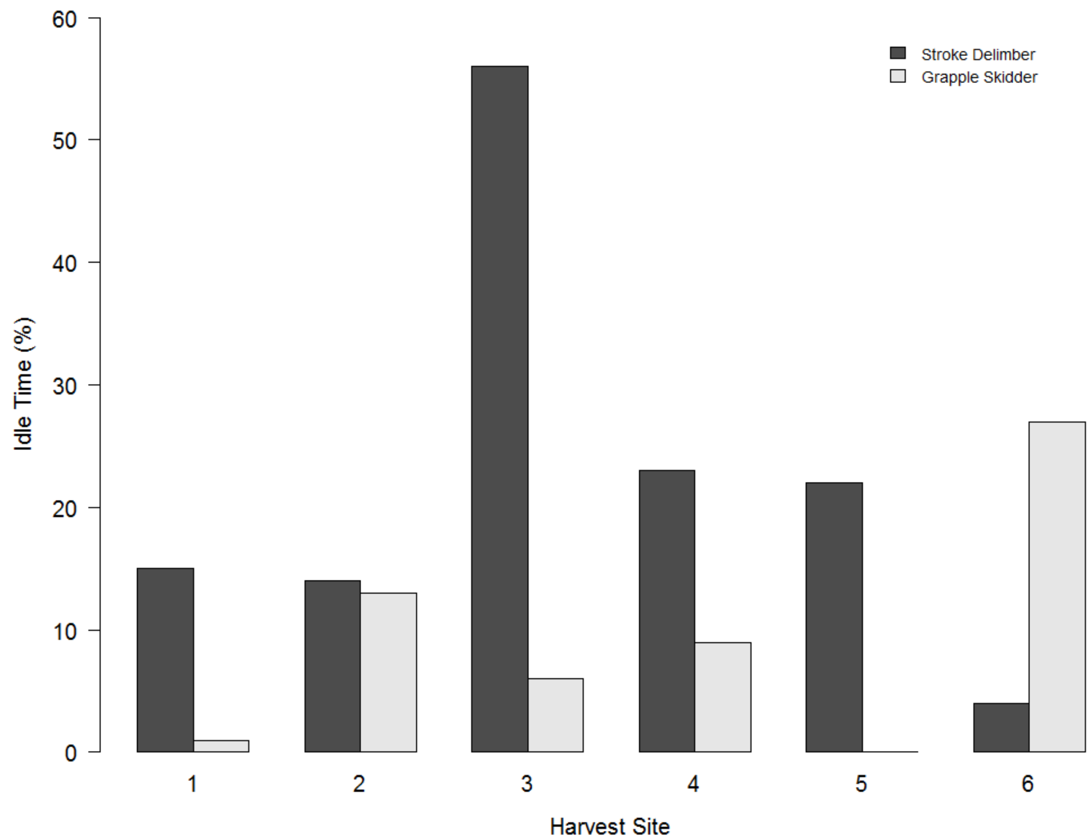

Figure 1.3: Observed percent idle time for stroke delimber and grapple skidder from six different harvest sites as recorded between May and August 2012 by Hiesl (2013). The sites represent a common range of site and stand conditions in Maine.

With the feller-buncher working independently, and mostly days ahead of a grapple skidder, we can therefore identify the interaction of the grapple skidder and the stroke delimber as the bottleneck in most whole-tree harvesting systems. Research has further shown that the processing time of stroke delimbers is negatively impacted when processing hardwoods (Hiesl 2013). As with harvesters (Glöde 1999), the generally larger branch size of hardwoods, but also some softwood species such as eastern Hemlock, increases the processing time for stroke delimbers as well. Maine's forest land consists of over 50% of hardwood forest types (McCaskill et al. 2011), and land managers and logging contractors alike have to deal with the negative impact of hardwoods on harvesting productivity. This highlights the importance to understand the impact of an increasing hardwood component on stroke delimber and grapple skidder idle time.

Presently, there are three computer simulation methods commonly used for modeling different abstraction levels, such as System Dynamics, Discrete Event, and Agent Based (Borshchev and Filippov 2004). All methods have their strengths and weaknesses. ABM is versatile and can be used in a range of low to high abstraction levels, depending on the needs of the simulation. With ABM the focus is on individual objects (agents) that can vary in their scope and nature, such as people, vehicles, machines, customers, competing companies, etc. (Borshchev and Filippov 2004). The novel aspect of ABM is that behavior rules of individual agents and their interactions can be specified. This is the most outstanding difference of ABM from the other simulation methods, and makes this method especially useful in modelling forest harvesting with different machines. We have chosen an agent-based modeling technique because we are focused on individual agents (stroke delimber and grapple skidder) with unique and interacting behaviors.

Epstein (1999) described five characteristics of agent based modeling (ABM), of which at least one should be met, to ensure a successful application of ABM to a certain research question: (1) heterogeneity of the agents, (2) autonomy of the agents, (3) explicit space, (4) local interactions, and (5) bounded rationality. All five characteristics hold true in our simulation of stroke delimber and grapple skidder interactions. Although often used in social sciences, agent based modeling (ABM) also experiences widespread popularity among other disciplines (Bazghandi 2012; Gilbert 2007; Manson 2003). Examples include traffic simulations in metropolitan areas (Bazghandi 2012), and the simulation of harvesting scenarios in mangrove forest plantations (Fontalvo-Herazo et al. 2011). There is growing interest among researchers in using agent based models to explore ecological and silvicultural consequences of harvesting prescriptions (Arii et al. 2008) and to investigate the harvest decision making of forest landowners (Leahy et al. 2013). Our model will expand the use of agent based models to include forest operations research questions at the machine level.

Due to the large amount of data generated by this model and the multitude of research questions that can be asked we will focus in this paper on a detailed model description and investigate the effect of an increasing hardwood component on stroke delimber and grapple skidder idle time and productivity. A separate analysis of skidding distance, payload, and a two skidder scenario is detailed in Chapter 2.

METHODS

To better understand the interactions of stroke delimber and grapple skidder and to test new processing techniques we create the stroke delimber and grapple skidder agent based model (SDGS-ABM). The model was created using the agent based modeling tool NetLogo v5.0.5 (Wilensky 1999). We present this model following a modified version of the overview, design concepts, and details (ODD) protocol (Grimm et al. 2010; Grimm et al. 2006). The ODD protocol represents a well-adapted standard to communicate model descriptions consistently and effectively. The model has been developed in English units as the model is based on harvesting conditions in the Northeastern US and intended for the use in this region.

Purpose

The purpose of the model was to investigate the productivity of stroke delimber and grapple skidder working on harvest tracts of different sizes and removal intensities. The goal was to gain knowledge about the productivity and time consumption of four different skidding and delimbing behaviors (Table 1.1) to gauge the benefit and applicability of different system configurations.

Balsam fir (*Abies balsamea* (L.) Mill.) and red maple (*Acer rubrum* L.) were used as reference species for softwood and hardwood species, respectively, as these are two common species in Maine’s forests. Results from this model will be used to determine whether a change in system configuration and operator communication features would in fact increase machine productivity and reduce waiting times.

Table 1.1: Description of four different skidding and delimbing behaviors as included in the model.

Scenario	Description
1	In this scenario there is no active communication between the grapple skidder and stroke delimber. There is no optimization of skidding times through additional processing information. This is our baseline scenario.
2	In this scenario the stroke delimber knows the processing time for each bunch. In addition, the grapple skidder knows the traveling time for each bunch. Through the combination of the two sources of information the grapple skidder is able to select a bunch that will keep the waiting time for the stroke delimber at a minimum.
3	This scenario uses the same information as scenario 2, but in addition a process improvement feature for the stroke delimber is introduced. The processing time for each tree is reduced between 0.5 and 8 seconds to improve the stroke delimber productivity.
4	This scenario is similar to scenario 1 but uses two grapple skidders instead of one. This will increase the stroke delimber productivity by reducing the waiting time. (Details of the analysis of Scenario 4 are discussed in Chapter 2)

Entities, State Variables, and Scales

The model has four kinds of entities: grapple skidders, stroke delimbers, bunches, and square patches of land. Grapple skidders and stroke delimbers have no state variables, however, several pieces of information are recorded in global variables after each skidding cycle (Table 1.2). Each bunch consists of a differing number of trees with different diameters, and has two state variables: one that describes the bunch size , and another for the distance of the bunch to the landing, given a previously laid out trail network exists. Patches are described by their patch size and the patch landuse (such as trail or forest land).

The grapple skidder is a moving agent that travels along a trail network and collects one bunch at a time. A bunch is located along the trail network with a user-defined spacing between individual bunches. Bunches can only move when a grapple skidder picks them up and carries them to the landing, where they are processed by the stroke delimber. The stroke delimber is a static agent that sits permanently at the landing and processes individual trees from a bunch. Several environmental variables are defined by the user: length of the main trail, removal per acre, bunch spacing, hardwood content, delimber processing time improvement, stroke delimber machine rate, and grapple skidder machine rate. The user can further choose to create bunches with random or equal sizes, and also selects one of the four behavioral scenarios. Total width of the harvest tract is predefined at 612 feet. The road is 36 feet wide and next to a landing of 144 feet by 300 feet. The trail system consists of one main trail with side trails leaving the main trail in a 45 degree pattern and 60 foot trail spacing. The temporal extent of the model is the time it takes to skid and process all bunches along the trail.

Table 1.2: State and global variables of the four model entities.

Entity	State / Global Variable
Grapple Skidder	Total waiting time in minutes Current waiting in minutes Current skidding time in minutes Total number of bunches skidded
Stroke Delimber	Total waiting time in minutes Current waiting time in minutes Current delimbing time in minutes Total number of bunches delimbed
Bunch	Bunch size in tons Distance to the landing along trail in feet
Patch	Patch size (12 feet x 12 feet) Landuse type (trail, forest, landing, road)

Process Overview and Scheduling

During the model setup the following information is calculated based on the user chosen input variables and displayed in output monitors: area harvested (acres), average bunch size (tons), length of main trail (feet), maximum skidding distance (feet).

The trail system is put in place during the model setup by the submodel “create trail” and populated with bunches by the submodel “place bunches”. The model further includes the following processes that are executed in this order during each time step.

Skid bunch: The grapple skidder moves to the nearest bunch along the main trail and brings the bunch back to the landing. Once the main trail is cleared the skidder moves to the nearest bunch amongst the side trails. If the user selects scenario 2 or 3 the skidder moves to the farthest bunch that is within the distance that the skidder can travel during the time the delimber takes to process the previous bunch. The total skidding time is calculated using a regional grapple skidder cycle time function (Table 1.3).

Table 1.3: Description of values used in this model, including source of information.

Description	Value	Source
Cycle time equation for grapple skidder	Cycle Time (min) = exp(1.618 + 0.0005 x OneWayDistance (ft))	Hiesl and Benjamin (2013c)
Cycle time equation for stroke delimber	Cycle Time (min) = exp(-1.247 + 0.099 x DBH (in) – 0.135 x SpeciesGroup (1 = softwood, 2 = hardwood))	Hiesl and Benjamin (2013c)
Standard deviation for the spread of bunch sizes across a harvest site	0.8	unpublished results of Hiesl (2013)
Lamda-value for a poisson distribution that represents the distribution of tree diameters in a given bunch	8.43	unpublished results of Hiesl (2013)
Average removal intensity used in this study (in tons/acre)	40	unpublished results of Hiesl (2013)
Average spacing between individual bunches (in ft)	48	unpublished results of Hiesl (2013)

Skid Two Bunches: This process is only called for in scenario 4 when two grapple skidders are skidding wood from the harvest tract. The process is similar to "skid bunch", however, each skidder delivers wood to their own drop zone at the landing, so that the stroke delimber has two bunches to work with.

Process bunch: During the first run of the "skid bunch" process the stroke delimber has no trees to process and therefore has to wait for the skidder to come back. After the skidder brings a bunch the sub-model "select trees" calculates the number of trees and individual tree sizes for the bunch. The stroke delimber then processes one tree at a time. The time consumption for each tree is calculated using a regional cycle time function for stroke delimber estimated from empirical data (Table 1.3).

Update output: This process updates all output monitors and advances time accordingly. Output monitors record the following information: total skidded volume, total time consumption, current grapple skidder time for this cycle, current grapple skidder waiting time for this cycle, total grapple skidder waiting time, grapple skidder waiting time in percent of total time, current stroke delimber time for this cycle, current stroke delimber waiting time for this cycle, total stroke delimber waiting time, stroke delimber waiting time in percent of total time, system productivity (tons/PMH), grapple skidder and stroke delimber total cost of operation ($), grapple skidder and stroke delimber harvest cost ($/ac), and grapple skidder and stroke delimber unit cost of production ($/ton).

Design Concepts

The basic principle is to simulate the interactions between grapple skidders and stroke delimbers in four different scenarios that include (1) a "normal" harvest, (2) a harvest with perfect knowledge of processing times, (3) a harvest with perfect knowledge of processing times and increased delimbing speed, and (4) the use of two grapple skidders. The choice of perfect knowledge is based on potential technological developments (such as enhanced communication and location-tracking technology) within equipment cabs to accurately estimate processing times.

Grapple skidders interact with bunches by removing them from the trail and skidding them to the landing. The stroke delimber processes one bunch, tree by tree, and in scenarios 2 and 3 estimates the processing time for each bunch. In these scenarios grapple skidder and stroke delimber interact directly with each other by exchanging information which alters the skidding behavior of the grapple skidder.

The bunch size is randomly chosen using the average bunch size - calculated based on the user chosen removal intensity, bunch spacing, and length of trails – and a previously observed standard deviation of common bunch sizes (Table 1.3). The tree diameters in each bunch were randomly chosen using a previously observed Poisson distribution (Table 1.3). A differentiation is made between hardwoods and softwoods, as tree heights and volumes at a given diameter are different.

Initialization

The simulated harvest tract is created with a fixed width of 51 pixels (612 feet) and a user defined length of between 40 and 210 pixels (480 to 2520 feet). The main trail is located in the center of the harvest tract parallel to the length of the harvest tract. Side trails join the main trail at 45 degree angles and a spacing of 5 pixels (60 feet). Bunches are placed along the trail system with user defined bunch spacings. One grapple skidder and one stroke delimber are created in scenarios 1 to 3, while a second grapple skidder is created in scenario 4. All equipment starts at the landing.

All time and productivity counters are set to zero. Each bunch has a randomly assigned bunch volume and a distance to the landing calculated based on their location on the trail. The harvest area in acres is calculated during the setup based on the trail system and a 25 foot swath on each side of the trail to represent feller-buncher reach. The average bunch size, main trail length, and maximum skidding distance are also calculated during the setup.

Submodels

Create Trail: The main trail is placed at the center of the harvest tract with 26 pixels (312 feet) to the left and right to the harvest tract boundary. Starting at the landing the side trails join the main trail at a 45 degree angle and reach all the way to the boundary. The spacing between trails is 5 pixels (60 feet).

Place Bunches: The number of bunches on the main trail and for each side trail are calculated during the trail setup based on the user defined bunch spacing. Based on harvest area, removal intensity, and number of bunches the average bunch size is calculated. Using a standard deviation of 0.8 tons (Table 1.3) the bunch size for each bunch is randomly drawn. All bunches are placed at the end of each side trail and trails are then populated with bunches towards the main trail. This feature represents common harvesting techniques used in whole-tree harvesting in Maine. During the placement the model periodically checks the total bunch size of all bunches placed on trails and compares it with the total removal for the harvest tract and makes the necessary adjustments in bunch size if the total bunch size is too high.

Select Trees: When a bunch is being processed by the stroke delimber the bunch size is divided into softwood (SW) and hardwood (HW) size based on the hardwood content chosen by the user. SW and HW tree diameters are chosen from a Poisson distribution (Table 1.3). Each diameter is associated with an average tree size. Individual tree sizes were calculated using Honer's equations (Honer 1967). Balsam fir (*Abies balsamea* (L.) Mill.) and red maple (*Acer rubrum* L.) were used as reference species for softwood and hardwood, respectively. We used average tree heights from unpublished data of Hiesl (2013) for the calculations (Table 1.4). The tree size of each tree is added up until the bunch size for SW and HW is reached.

Graphical User Interface

To increase the usability of this model a user friendly interface was created (Figure 1.4). This interface includes several sliders with pre-defined options to adjust various input variables such as the removal per acre, bunch spacing, or hardwood content. Four groupings of output monitors exist to show the user (1) important time information during each skid, (2) cumulative waiting time information, (3) cumulative productivity and cost information, and (4) general harvest tract information. A full list of output variables can be found in the previous "Update output" section.

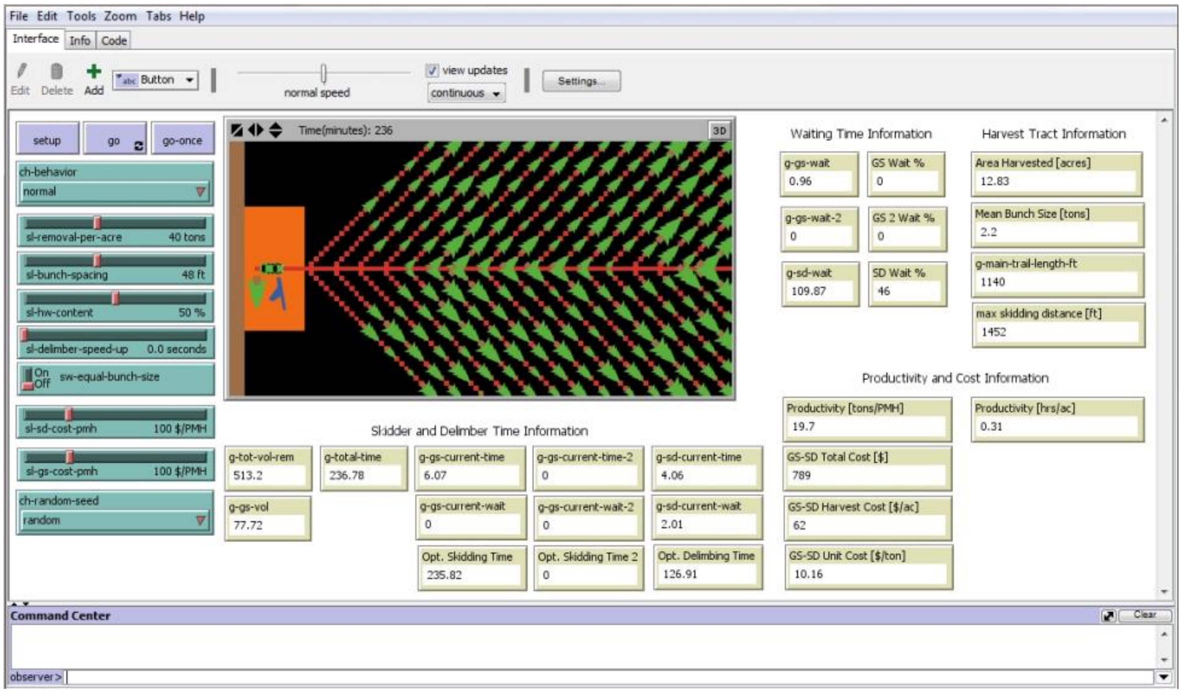

Figure 1.4: Screenshot of the model interface.

Simulation Analysis Methods

To analyze the effect of hardwood component on stroke delimber and grapple skidder idle time the model was run using an average bunch spacing of 48 ft (Table 1.3), an average removal intensity of 40 tons/acre (Table 1.3), and varying degrees of hardwood composition (Table 1.5). To analyze the effect of the different behavioral scenarios we also run this setup for Scenarios 1 to 3. We used NetLogo's BehaviorSpace module to run each configuration. The output was analyzed using the statistical software package R (R Core Team 2015). To analyze the effect of bunch spacing and removal intensity on the baseline scenario (Scenario 1) we included a total of six bunch spacings and six removal intensities in the simulation.

Table 1.4: Tree diameter, height, and volume for softwood and hardwood trees used in the model.

Dbh (in)	Tree height (ft)	Tree volume (tons)	
		Softwood	Hardwood
4	37	0.078	0.071
5	43	0.138	0.126
6	48	0.215	0.201
7	53	0.315	0.280
8	56	0.429	0.408
9	59	0.563	0.540
10	61	0.711	0.657
11	63	0.880	0.854
12	64	1.059	1.030
13	66	1.270	1.241
14	70	1.532	1.512
15	74	1.825	1.819
16	76	2.112	2.116
17	78	2.425	2.440
18	78	2.719	2.736
19	79	3.054	3.080
20	86	3.570	3.658

Table 1.5: Variables used in the simulation to analyze the effect of hardwood component on stroke delimber and grapple skidder idle time.

User-Defined Variable	Min-Value	Max-Value	Step-Size	# values tested
Scenario	1	3	1	3
Removal per acre (tons)	40	40	0	1
Bunch spacing (ft)	48	48	0	1
Hardwood content (%)	0	100	10	11
Max One-Way Skidding Distance (ft)	732	2,892	240,	10
			Parameter Combinations	**150**
			Simulations	**15,000**

Sensitivity Analysis

A local sensitivity analysis was conducted based on the Railsback and Grimm (2012) analysis structure. The goal of any sensitivity analysis is to understand how sensitive a model is to small changes in the value of input variables. Such information can help to verify the model structure by assessing whether or not specific sensitivities exist in the model. A local sensitivity analysis changes one input parameter at a time and therefore represents the sensitivity of such one parameter to a baseline of the other input parameters only. In contrast to that, a global sensitivity analysis changes several input values at the same time over a wide range of baseline scenarios to fully investigate the sensitivity of a model. For this local sensitivity analysis we increased the input values of three variables (skidding distance, hardwood component, bunch size) by 10% to calculate the sensitivity value. The baseline values of the three input variables reflect average skidding and delimbing conditions in Maine. Baseline values were determined from unpublished data of Hiesl (2013). The three input variables were chosen based on their known influence on system productivity from other research.

SIMULATION RESULTS

Results of baseline scenario (Scenario 1) of the model showed that the system productivity of grapple skidder and stroke delimber was heavily influenced by skidding distance, removal per acre and bunch spacing (Figure 1.5). System productivity increased with increasing removal intensity, increasing bunch spacing and decreasing skidding distance. Bunch spacing ($p<0.001$) and removal intensity ($p<0.001$) clearly indicated a difference in system productivity.

The analysis of the effect of hardwood component on stroke delimber waiting time showed that there is a reduction in waiting time with increasing hardwood component ($p<0.001$). This reduction is up to 13% at short skidding distances and decreases to 7% at the longest skidding distance (Figure 1.6). No difference was found in the stroke delimber waiting time between Scenario 1 and Scenario 2 ($p=0.999$), however, there was a difference between Scenario 3 and the other two scenarios ($p=0.004$). Grapple skidder waiting time was not affected by the change in hardwood component and stayed below 1%.

Even though there is a decrease in stroke delimber idle time with increasing hardwood component, our results show that the system productivity is not affected by hardwood component ($p=0.922$). Further, there was no difference ($p=0.998$) found in system productivity between the three tested scenarios (Figure 1.7). Thus, the productivity stays the same whether or not the hardwood component increases, a GIS/GPS based communication system is used (Scenario 2), or the stroke delimber increases processing speed (Scenario 3). The only influential factor on system productivity is skidding distance ($p<0.001$). An increase in skidding distance causes a decrease in system productivity.

Waiting time data from Figure 1.1 shows that a stroke delimber generally waits between 4% and 56% of the time, while a grapple skidder waits between 0% and 27%. These values have been collected from harvest sites with removal intensities ranging from 25 tons/acre up to 67 tons/acre. The waiting times produced by this model (Figure 1.8) are similar to the range of observed waiting times. This shows that the model is an accurate representation of a stroke delimber and grapple skidder harvesting system.

Model Evaluation

The relationship between system productivity and site specific variables such as skidding distance and removal intensity, in combination with the correct representation of waiting times supports the assumption that this model is well calibrated. To increase the usefulness of this model to other researchers and the logging community, however, it is crucial to test the model for its sensitivity to parameter combinations.

Local and global sensitivity analyses were used to evaluate the sensitivity of our model to a change in input variables. Results showed that average bunch size had the greatest impact on system productivity, followed by skidding distance (Table 1.6). The impact of hardwood content on system productivity was very low compared to the other two input variables. Such an analysis is a snapshot of the effect of input variables on system productivity based on baseline conditions that represent average harvesting conditions in Maine. To gain more insight of the effect of these variables based on a variety of harvesting conditions we conducted a global sensitivity analysis (Figure 1.9).

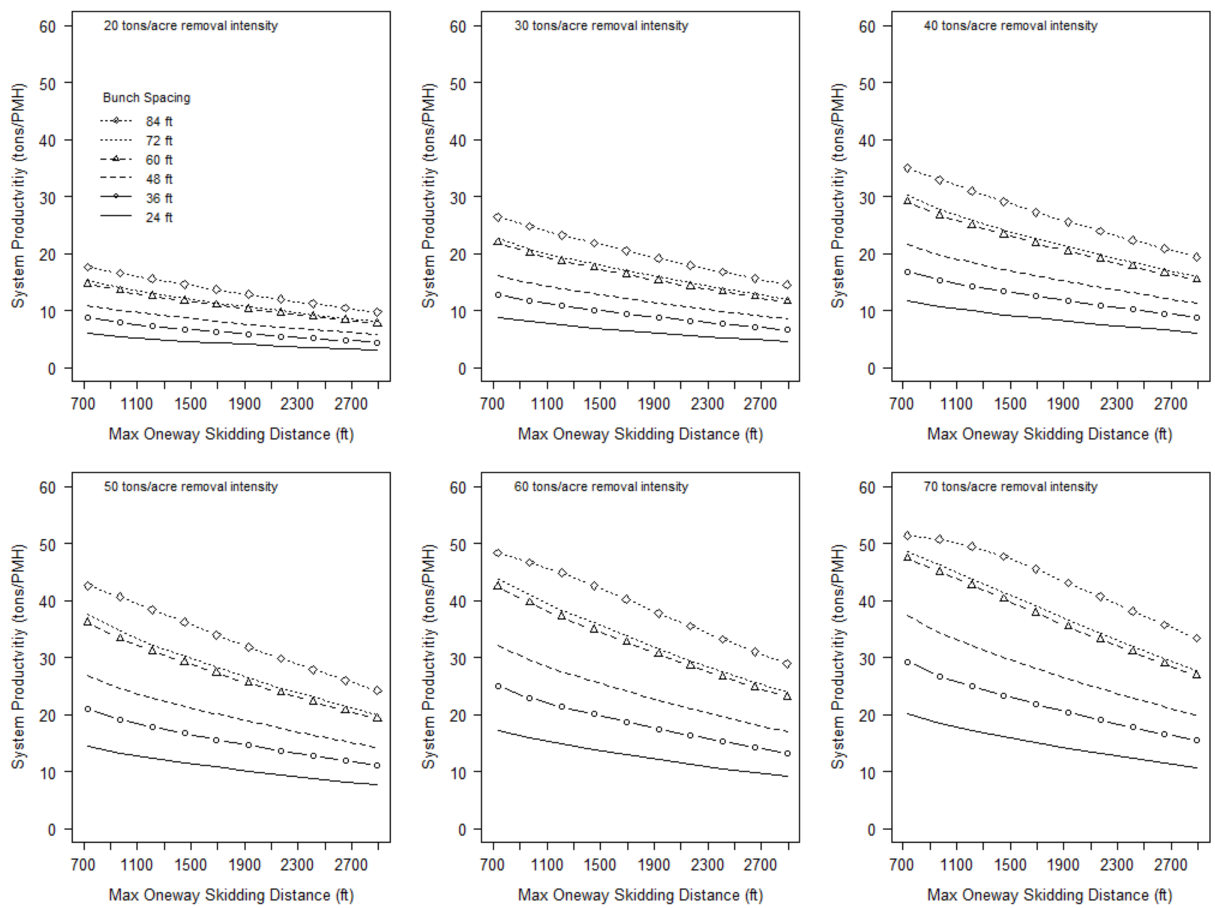

Figure 1.5: Grapple skidder and stroke delimber system productivity based on removal intensity and bunch spacing with a 50% hardwood component when using the baseline scenario (Scenario 1). PMH = productive machine hours.

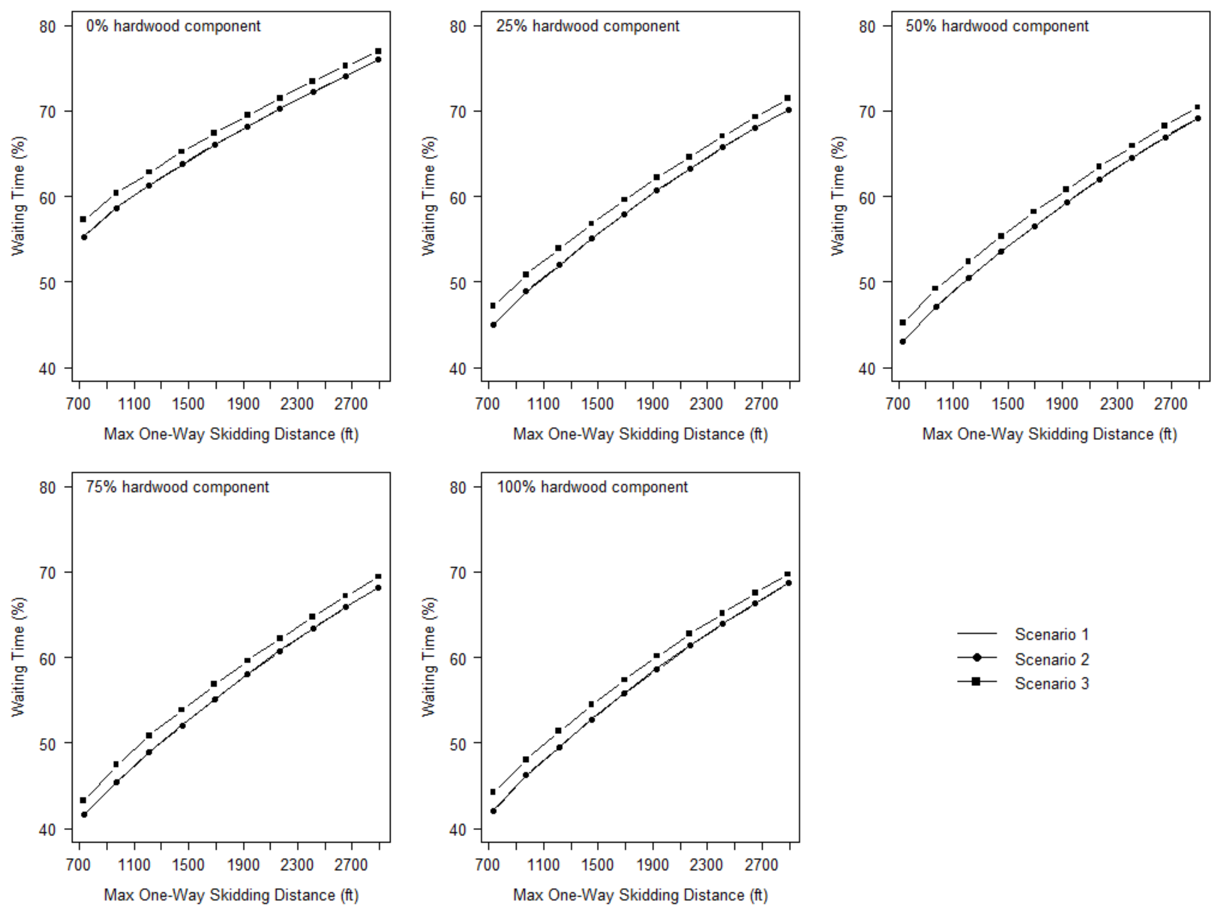

Figure 1.6: Stroke delimber waiting time based on various hardwood components and an average bunch spacing of 48 ft and a removal intensity of 40 tons per acre. No difference was found between Scenario 1 and Scenario 2 and both lines are approximately on top of each other.

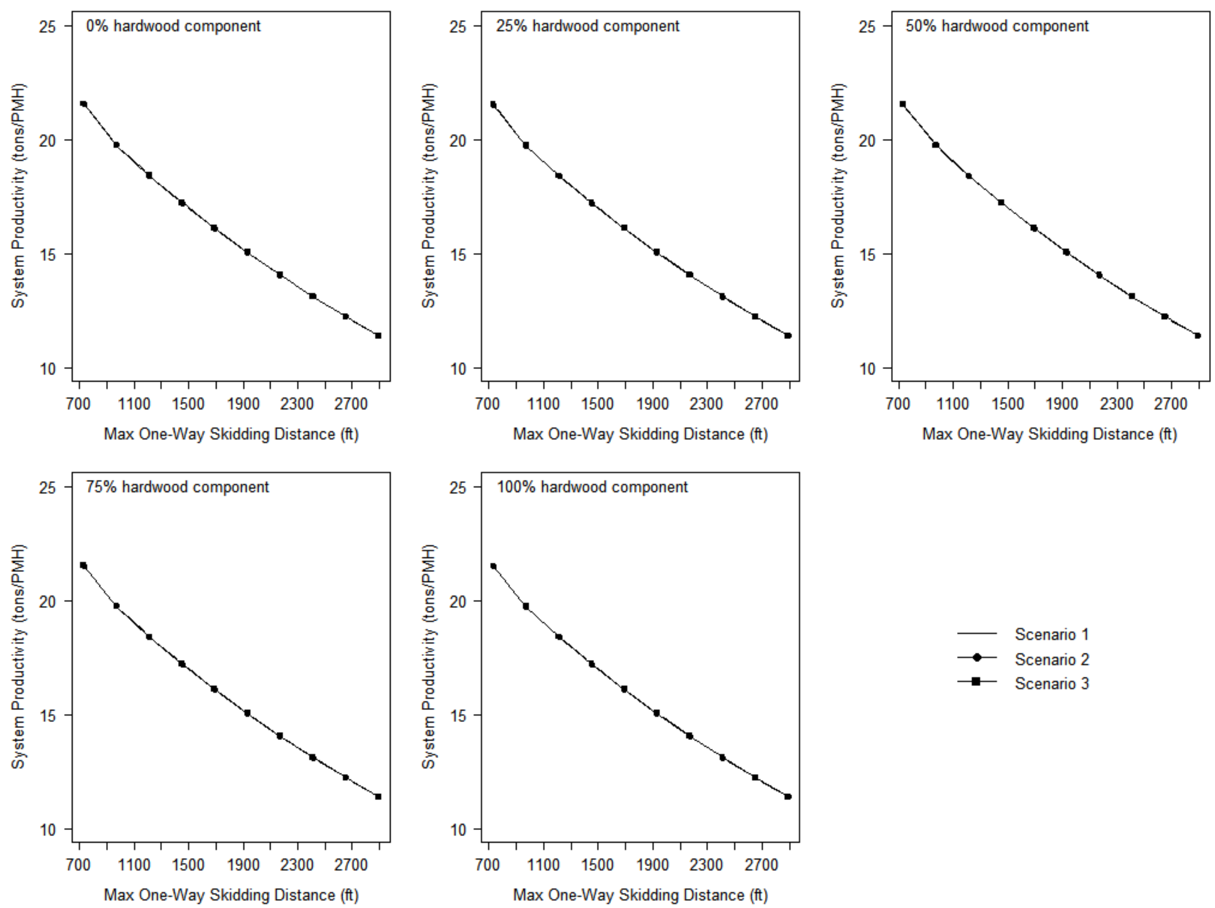

Figure 1.7: System productivity of a grapple skidder and stroke delimber system based on various hardwood components and an average bunch spacing of 48 ft and a removal intensity of 40 tons per acre. The productivity of all three scenarios is similar and thus the individual lines are overlaying each other.

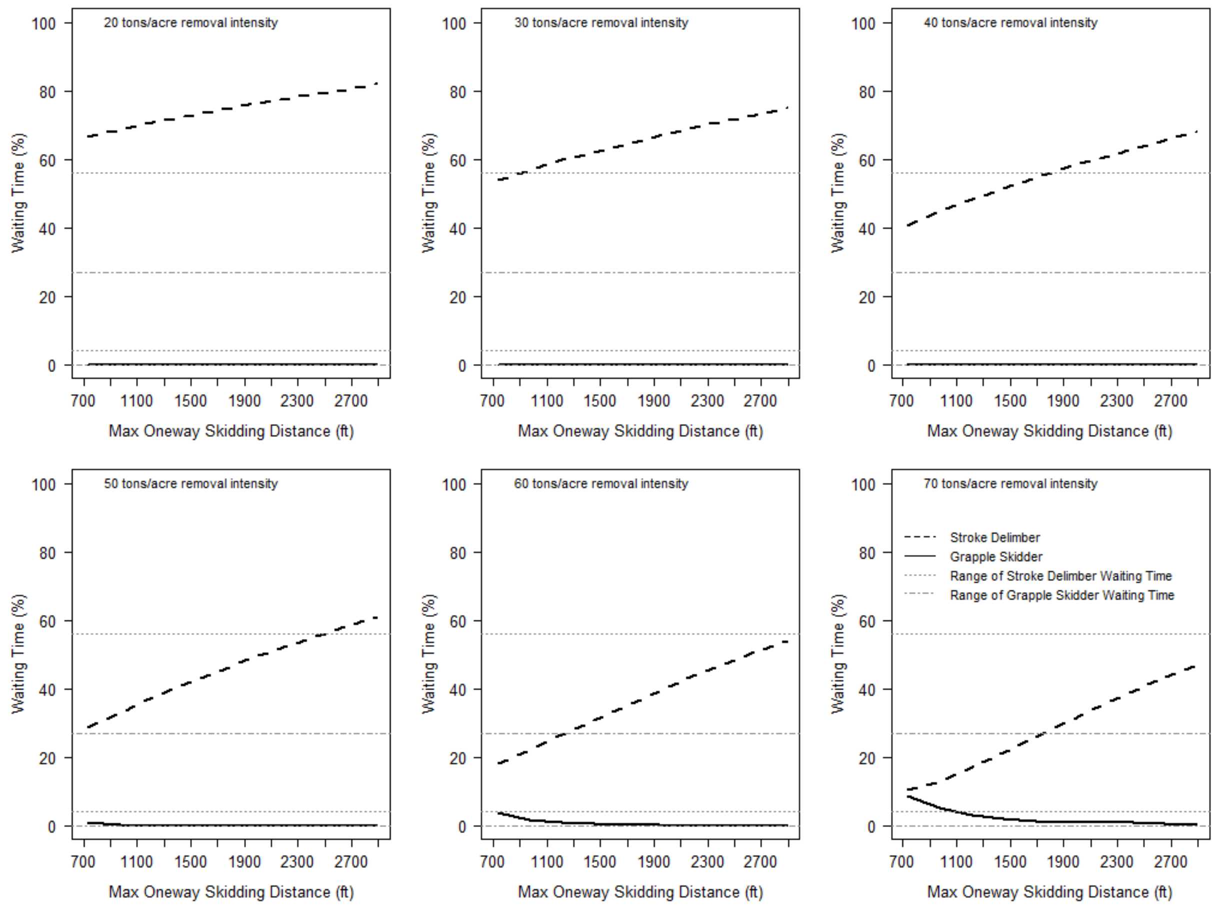

Figure 1.8: Waiting time for grapple skidder and stroke delimber based on skidding distance and removal intensity.

The global sensitivity analysis shows that the effect of bunch size on system productivity is less pronounced at short skidding distances and high bunch sizes and increases with skidding distance and a reduction in bunch size. The effect of skidding distance on system productivity intensifies with an increase in skidding distance. This effect, however, is reduced with an increase in bunch size. A higher softwood component increases system productivity at short skidding distances and high bunch sizes but loses intensity with longer skidding distances.

Table 1.6: Local Sensitivity Analysis of three input variables.

Parameter	Reference value	Sensitivity value	Change in productivity (%)	Change in productivity (tons/PMH)
Skidding Distance (ft)	1,380	-10.51	-4.82	-1.05
Hardwood Content (%)	50	-0.20	-0.09	-0.02
Average Bunch Size (tons)	3.0	22.44	10.29	2.24

Note: Parameter values were increased by 10%.

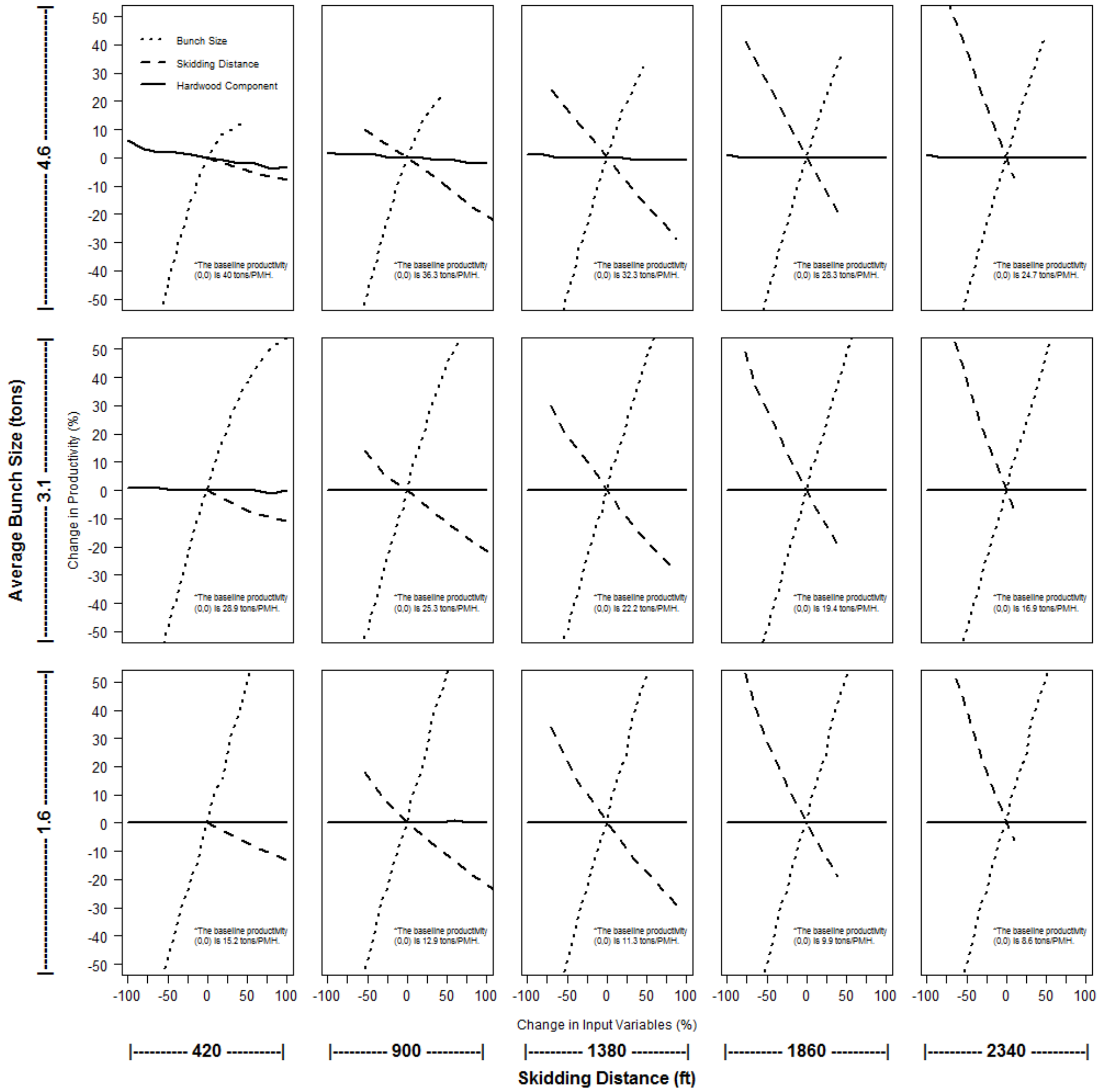

Figure 1.9: Global Sensitivity Analysis of three input variables based on baseline conditions consisting of a variety of skidding distances (x-axis), average bunch sizes (y-axis), and a 50% hardwood component.

DISCUSSION

The use of agent based modeling in forestry is fairly new. Agent-based modeling has been used to investigate and model harvesting decision making of landowners (Leahy et al. 2013), simulate landscape-scale forest ecosystem dynamics (Seidl et al. 2012), and model harvesting scenarios in mangrove forest plantations (Fontalvo-Herazo et al. 2011). Our model is one of the first to apply an agent-based approach to production forestry in a developed country. We further created a graphical user interface in NetLogo (Wilensky 1999) that allows users to vary input variables such as removal intensity, hardwood content, and bunch spacing.

This model uses cycle time equations specifically developed for harvesting systems in Maine. In addition to that, all the values and probabilities used in this simulation are from unpublished data of a harvesting cycle time and productivity study by Hiesl (2013). Such empirical data increases the applicability and plausibility of this model. For example, the sensitivity analysis returned skidding distance and bunch size as important factors affecting system productivity. Skidding distance is a well-known factor that affects skidder productivity and has been reported by several researchers (Hiesl 2013; Han et al. 2004; Kluender et al. 1997; Andersson and Evans 1996). Bunch size, or payload, has also been described as a factor influencing grapple skidder productivity (Wang et al. 2004; Kluender et al. 1997). As our model aligns with this previous literature we are confident that the core model dynamics are accurate and well calibrated including the relationship between input variables and system productivity. With the open source characteristic of this model it is possible for other researchers to extend the existing model to include other harvesting systems and management treatments. Such extension could include further calibration, development of other submodels, or the inclusion of new data. The benefit of our agent-based model is that these changes are relatively simple to implement.

Our results showed that an increase in hardwood component can reduce the waiting time for a stroke delimber but has no effect on the waiting time of a grapple skidder. This result is not surprising as the literature indicates that the stroke delimber processing time is higher for hardwood than it is for softwood species (Hiesl 2013). One reason for this increase in time consumption can be found in the larger branch size and the increased number of forks in the crown. Research with harvesters showed that a large branch size negatively affected processing speed and productivity (Glöde 1999). A stroke delimber uses a similar movement to delimb trees as a harvester does, so it is a reasonable assumption that the same applies here. With the lowest waiting time being approximately 40% it is not surprising that the grapple skidder waiting time is close to zero. Even though there is a negative effect of hardwoods on processing speed, there was a positive effect on waiting time. This is due to the large number of excess time that a stroke delimber has before the grapple skidder can deliver a new bunch. This excess time can be used to process hardwood trees without increasing the idle time, as more of the excess time is used to process hardwoods. The presented simulation, however, was done based on average bunch spacing and removal intensity. In many situations a land manager or logging contractor has to deviate from these standards and may encounter a more positive or negative effect of a change in hardwood component.

A decrease in stroke delimber idle time, however, does not necessarily mean that there will be an increase in system productivity. Our results showed that hardwood component did not affect system productivity. This can be attributed to the fact that in the presented case the skidding time is not affected by the species mix in each bunch and thus stays the same regardless of hardwood component. This further means that the overall time consumptions stays the same, even though the stroke delimber spends less time waiting for a new bunch. Research indicated that grapple skidder productivity is affected by payload (Hiesl 2013; Li et al. 2006; Wang et al. 2004; Kluender et al. 1997) and thus the results might be different when changing the average bunch size in our simulation. In our analysis, however, we were interested in the effect of varying hardwood components on system productivity and machine idle time when operating under average harvesting conditions. The fact that there is no effect on system productivity therefore indicates that mixed-wood and hardwood stands in Maine can be treated without losing any productivity or increasing harvest costs.

When looking at the system productivity the results further showed that there is no difference in productivity between the three tested scenarios. The surprise was that the use of GIS/GPS (Scenario 2) did not result in any production increase. One reason for this might be the use of one main trail only. This fact limits the grapple skidder in the number of bunches that can be chosen to minimize stroke delimber waiting time. Another reason might be the chosen behavior rule of selecting the bunch that is farthest away but does not cause any more stroke delimber delay. This behavior rule did not include the clearing of the main trail first and thus limited the number of bunches that were accessible. The third scenario included an increase in processing speed of 1 second per tree. This increase in processing time resulted in an increase in stroke delimber idle time. This can be attributed to the fact that the grapple skidder was not delivering bunches any faster and thus the increased processing time left more time for the stroke delimber to wait for the grapple skidder.

In Figure 4, system productivity is shown for varying removal intensities and bunch spacings. Individual productivity curves are fairly uniformly distributed among the different bunch spacings with the exception of the 60 and 72 ft bunch spacing. These two productivity curves are very close and almost overlay each other. The reason for this lies in the bunch placing process of the simulation. Bunches were placed on a side trail starting at the end of a trail and then spacing them by the user defined bunch spacing. For all bunch spacings the number of bunches per side trail decreased with increasing bunch spacing, with the exception of the 60 and 72 ft bunch spacing. In this special case, the number of bunches in each side trail stayed the same, with the exception of a few side trails at the end of the harvest block. Lengthening or shortening the side trails only shifted this process to a different pair of bunch spacings. It is important to notice, however, that this effect also happens at real harvest sites, and thus a change in bunch spacing might not have the sought after effect of increasing bunch size.

Extensions of this work can include the application of the model to investigate system productivity change, and skidder and delimber wait time that emerge from real world harvesting scenarios. For instance, an analysis might seek to answer the question whether or not an investment in various types of communication or spatial awareness technology will result in any productivity gains across varying stand and site conditions, and if so, whether or not this investment will pay for itself during the lifetime of these machines. Further economic calculations should include the unit cost of production as a measure of applicability of any system in the real world at the current market conditions. Many additional alternative management configurations are also possible with an agent-based system because the design of machine behavior and machine-machine interaction is greatly simplified over traditional approaches.

CONCLUSION

Our conclusion is that under average harvesting conditions in Maine it does not pay to invest in a GIS/GPS based communication system, at least not with the modeled behavior rules for such a system. Further, increased harvested hardwood component, under these average harvesting conditions, does not affect system productivity. This leaves current market conditions as one of the remaining limitations of treating mixed-wood and hardwood stands in Maine.

Unless the system of grapple skidder and stroke delimber is de-coupled, logging contractors and land managers have to accept that under average harvesting conditions the stroke delimber will wait for trees to be processed at least 40% of its operational time. With machine rates upwards of $100 USD/PMH this means that over $40 USD/PMH are spent sitting at the landing and waiting for wood. This is money spent without getting any return. Clearly there is a need to find new ways to use these to machines to further reduce the waiting time of either machine and to limit to money spent on processes that do not return any revenue.

CHAPTER TWO:

CAN TECHNOLOGY HELP IMPROVE GRAPPLE SKIDDER AND STROKE DELIMBER INTERACTIONS? A SIMULATION APPROACH

ABSTRACT

In this paper we analyze the results of an agent-based model focusing on the interaction of a grapple skidder and a stroke delimber within a simulated harvest operation. Four different operational scenarios were tested to show whether it is possible to influence idle time, unit cost, and productivity of the system. The scenarios included a conventional skidding pattern where the main trail is cleared first, a modified skidding pattern assisted by GPS/GIS technology to reduce idle time, a change in delimbing behavior to decrease processing time by one second per cycle, and the use of two grapple skidders to increase utilization of the delimber. Results showed that stroke delimber idle time increases with increasing skidding distance, but decreases with increasing bunch size. The use of new technology and a change in stroke delimber processing speed did not drastically change percent idle time, productivity, or unit costs. Using an average harvesting scenario in Maine, there was only a minimal change in unit cost of production by using GPS/GIS technology. The use of two grapple skidders had the most influence on percent idle time, productivity, and unit cost for the system. Our conclusions are that an investment in new technology depends on the cost of the investment and the annual production to assess the full benefit of the investment. The use of two grapple skidders, however, resulted in the biggest benefits across most tested scenarios and should be considered as an improvement for a grapple skidder and stroke delimber system.

INTRODUCTION

Owning and operating harvesting equipment is very capital intensive, and one key goal of a logging business owner is to reduce and eliminate unnecessary costs. Such costs are often hidden in day to day operations and might not be easily identified without careful and focused observation. During the summer of 2012, researchers of the University of Maine conducted time and motion studies on several whole-tree harvesting operations and then developed regional cycle time and productivity equations (Hiesl 2013). It was apparent from the field observations that the interaction between grapple skidders and stroke delimbers often resulted in a high percentage of idle time for both machines (Figure 2.1). In most cases the grapple skidder was the bottleneck of the operation, and a high percentage of stroke delimber idle time was accumulated due to an insufficient supply of trees to the landing.

It is common practice in Maine to have a grapple skidder and stroke delimber work at the same harvest site. Generally the landings are only big enough so that one bunch at a time can be delivered to the stroke delimber. A bunch consists of an accumulation of trees that were cut by a feller-buncher and piled into a bunch of appropriate size to be moved by a grapple skidder. Such a set-up inevitably causes one machine to wait for the other at times. The stroke delimber waits when it has processed all the trees of the current bunch, and a new bunch has not yet been delivered. The grapple skidder waits when a bunch is skidded to the landing but the stroke delimber has not yet finished processing all the trees of the previous bunch. The interaction between grapple skidders and stroke delimbers has been simulated in the past with the result that waiting times between 20% and 40% of productive machine hours have to be expected due to the technical coupling of these machines (Polley 1987). Based on Polley's simulation, waiting times of between 10% and 15% could be achieved when one machine was fully utilized. The recommendation by Polley (1987) was that technological coupling should be avoided in the development of new equipment. Today, however, grapple skidder and stroke delimber are still very much dependent on each other, and are used extensively in harvest activities.

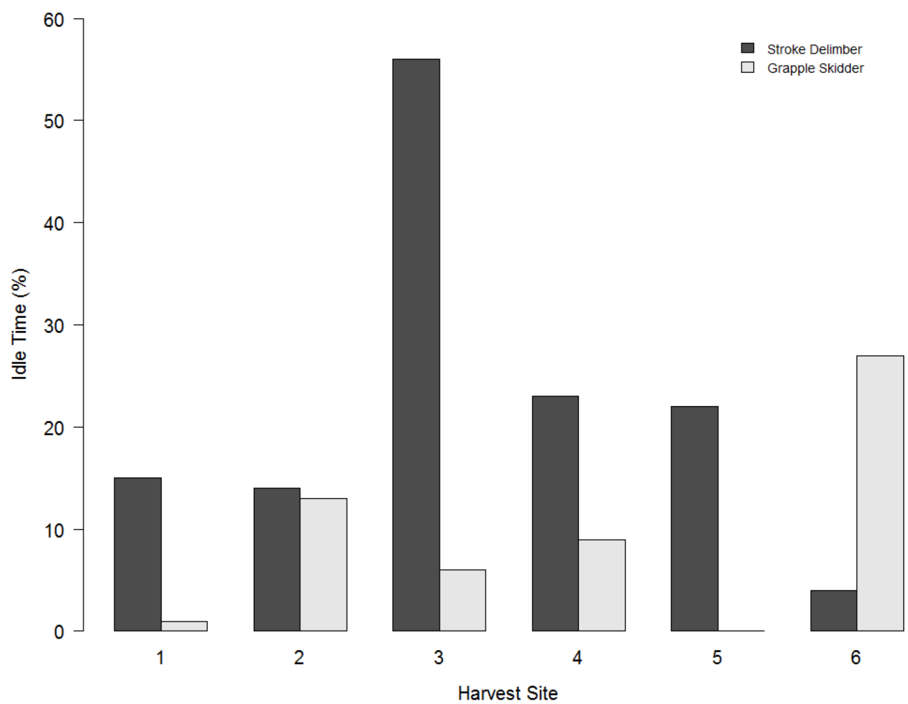

Figure 2.1: Stroke delimber and grapple skidder idle times as observed during a study by Hiesl (2013).

It is well established that skidding distance influences extraction time of a grapple skidder (Hiesl 2013; Han et al. 2004; Kluender et al. 1997; Gingras 1994). Additionally, a small bunch that consists of only a few trees will be processed by a stroke delimber in a shorter period of time than a large bunch with many trees. The combination of a small bunch size and a long skidding distance will subsequently lead to an increased idle time for the stroke delimber as this machine will process the bunch faster than a new bunch can be extracted. General practice in Maine is to extract all wood from the main trail first and then extract wood from the side trails. Other extraction practices, such as working more than one trail at a time to alternate between bunches that are close to the landing and further away however, have been observed by the authors as well. This particular practice could be greatly improved with the use of Geographic Information System (GIS) and Global Positioning System (GPS) technology. An agent-based computer simulation model was developed to compare system productivity for different wood extraction and processing practices.

Nowadays, three computer simulation methods are available for modeling different abstraction levels. These are System Dynamics, Discrete Event, and Agent Based Modeling. System Dynamics (SD) and Discrete Event (DE) are traditional simulation methods, whereas Agent Based Modeling (ABM) is a more recently developed modeling method (Borshchev and Filippov 2004). ABM is versatile and can be used to simulate low to high abstraction levels. With ABM, the focus is on individual objects (agents) that can vary in their scope and nature; agents can represent people, vehicles, machines, customers, or competing companies (Borshchev and Filippov 2004). The novel aspect of ABM is that behavior rules of individual agents and their interactions can be specified. ABM is commonly used in social sciences research (Janssen and Ostrom 2006; Bousquet and Le Page 2004), as system behaviors have not yet been mathematically formulated (Helbing and Balietti 2011), and an equations-based modelling technique would not be possible. In ABM the behavior of a system and its interactions are simulated by using multiple agents that interact with each other and the environment (Bazghandi 2012; Gilbert 2007; Brown 2006). Although often used in social sciences, ABM experiences widespread popularity among other disciplines (Bazghandi 2012; Gilbert 2007; Manson 2003). There is growing interest among researchers in using agent based models to explore ecological and silvicultural consequences of harvesting prescriptions (Arii et al. 2008) and to investigate the harvest decision making of forest landowners (Leahy et al. 2013).

The work environment and the work object of forest harvesting are quite variable (Polley 1987) and the assessment of costs, especially in natural stands, is rather complex (Abbas et al. 2013). The use of computer simulation models is often warranted as simulations are less expensive and faster than actual field trials (Winsauer and Underwood 1980; Bradley et al. 1976; Newnham 1968). Computer simulations have been well established for decades (Bazghandi 2012; Gilbert 2007; Polley 1987; Bradley et al. 1976), and early on, computer simulations have been found to be useful in studying present and future harvesting systems (Cavalli et al. 2011; Goulet et al. 1980a; Winsauer and Underwood 1980; Goulet et al. 1979; Newnham 1968). Computer simulations also provide valuable insight to potential relationships between system configurations and operating environments (Baumgras et al. 1993; Winsauer and Underwood 1980).

Our objectives with this study were to investigate (1) whether or not a high percentage of idle time for grapple skidder and stroke delimber is avoidable, (2) whether or not a change in skidding practice through the use of information from a GIS/GPS will reduce the idle time and unit cost by increasing system productivity, and (3) assess the productivity and unit costs of a de-coupled grapple skidder and stroke delimber system.

METHODS

Agent Based Model

We developed an agent based model to simulate the interaction between a grapple skidder and a stroke delimber in a whole tree harvest system. In such a system the feller-buncher cuts a main trail from which side trails disperse. The feller-buncher further forms bunches of trees and puts them into the trail, with the butt ends parallel to the trail facing the way of extraction. To represent this pattern in our model, we created one main trail in our simulation with side trails branching off at a 45 degree angle and a trail spacing of 18.3 m (Figure 2.2). In our model we developed three simulation scenarios using one grapple skidder and one stroke delimber and a fourth scenario using two grapple skidders and one stroke delimber. *Scenario 1* represents the baseline by using a common skidding approach, while *Scenario 2* is used to minimize the idle time of each machine. *Scenario 3* builds on Scenario 2 but adds an improvement in processing time by an average of one second per cycle. *Scenario 4* is similar to Scenario 1 but uses two grapple skidders instead of one. The time consumption for either machine was estimated using regional cycle time equations for grapple skidder and stroke delimber (Hiesl 2013; Hiesl and Benjamin 2013c).

Our model was developed using the agent based modeling tool NetLogo (Wilensky 1999). Each of the four scenarios was simulated 100 times for each combination of input variables to assess the impact on idle time, productivity, and unit cost. A full model description using the overview, design concepts, and details (ODD) protocol (Grimm et al. 2010; Grimm et al. 2006) can be found in Chapter 1. The model was developed using Imperial units but all measurements have been converted to SI units for this paper.

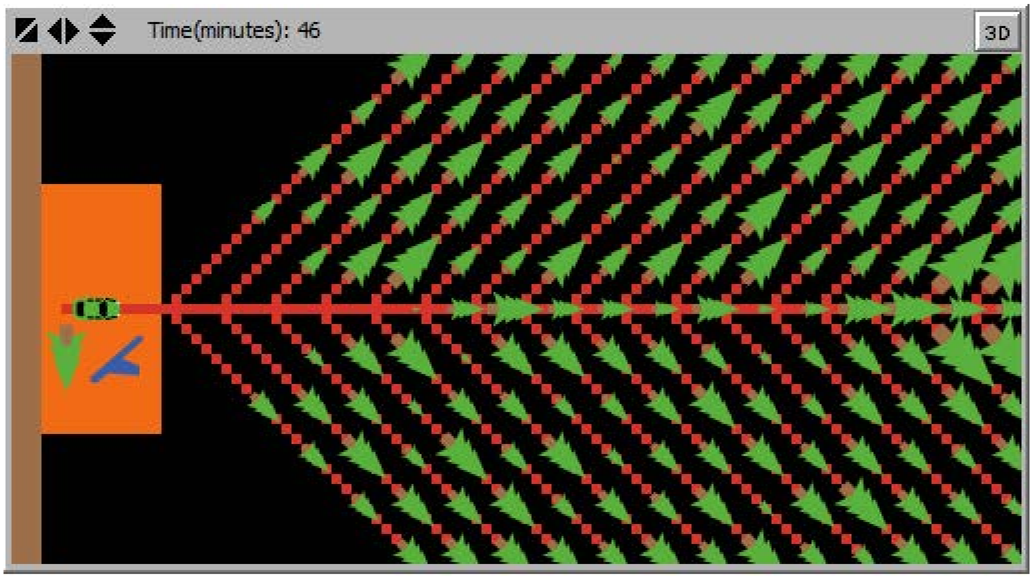

Figure 2.2: Screenshot of the trail pattern used in our model, consisting of one main trail and several side trails branching off at a 45 degree angle and a trail spacing of 18.3 m. Individual bunches (green trees on trails) have their butt ends facing towards the extraction route.

Tested Scenarios and Technical Improvements

Scenario 1. The general rule for grapple skidders was to extract bunches from the main trail first before extracting bunches from the side trails. After the extraction of one bunch by the grapple skidder the stroke delimber would process all trees in that bunch. The grapple skidder could not drop another bunch before the previous bunch was completely processed.

Scenario 2. Our assumption is that a GIS exists in which the feller-buncher operator marks every trail and every bunch on the trail. The GIS in the grapple skidder can estimate the travel time to each individual bunch. We further assume that the stroke delimber operator is able to accurately estimate the processing time for each bunch. With such information the grapple skidder operator is able to select the bunch that reduces the idle time for the stroke delimber the most. The implementation of such a

GIS/GPS system is technologically feasible but might not be readily available in practice. This scenario can also be viewed as the operators having perfect information on skidding and processing times and also working with perfect communication during the operations.

Scenario 3. This is an expansion of Scenario 2 and introduces best operating practices that allow the stroke delimber operator, on average, to decrease the processing time for each tree by one second. Results of a video analysis of stroke delimber operators showed that such a decrease in processing time is possible through a simple adoption of good processing practices (Benjamin and Hiesl 2013).

Scenario 4. In this scenario, two grapple skidders and one stroke delimber are using the same rules as laid out in Scenario 1. Observations of the authors included a frequent use of two grapple skidders and one stroke delimber at the same landing. We included this behavior to compare the idle time, productivity, and costs of such a system to the other three simulations.

Range of Conditions

Our model consists of four input variables that are changed for each simulation run and each of the four scenarios (Table 2.1). The variables “removal per acre” and “bunch spacing” were chosen as they influence individual bunch size, which has been shown to affect grapple skidder productivity (Hiesl 2013; Kluender et al. 1997). The processing time of a stroke delimber for hardwoods is longer than for softwoods (Hiesl 2013) and therefore the variable “hardwood content” was chosen to represent this difference in processing times in the simulation model. Skidding distance has been found a major factor influencing the extraction time of grapple skidders (Hiesl 2013; Kluender et al. 1997) and is represented in our model by the variable “maximum skidding distance”.

Table 2.1: Input variables and their range of values.

User-Defined Variable	Min-Value	Max-Value	Step-Size	# values tested
Removal per ha (tonnes)	67	157	45	3
Bunch spacing (m)	11	25	7	3
Hardwood content (%)	50	50	0	1
Max One-Way Skidding Distance (m)	223	880	73	10
			Parameter Combinations	**90**
	Number of Simulations (100 repetitions)			**9,000**

Data Analysis

A two-way analysis of variance (ANOVA) was used to compare the results of individual scenarios to detect significant changes in the four desired output variables of percent idle time (stroke delimber and grapple skidder), system productivity, and unit cost of production of the system. Percent idle time was calculated by dividing the observed idle time for each machine by the total time. System productivity is an output variable that is provided by the model used. Unit cost of production was calculated by dividing system cost by system productivity. System cost was calculated assuming a machine rate of 100 \$/productive machine hour (PMH) for grapple skidder and 130 \$/PMH for stroke delimber. Both machine rates represent the average of unpublished machine rate data from an early commercial thinning study in Maine by Benjamin et al. (2013).

To assess the cost savings in GPS/GIS technology we chose an example using average stand and site conditions in Maine. Based on observations from a study by Hiesl (2013) we chose a bunch spacing of 18 m, a removal intensity of 112 tonnes/ha, and an average skidding distance of approximately 365 m. To quantify the percent difference in unit cost of production between Scenario 1 and Scenario 2 we divided the unit cost of Scenario 2 by the unit cost of Scenario 1. Multiplying the difference in unit cost by the annual production of one whole-tree harvesting system (9,000 tonnes) approximates the annual cost savings achieved by using a GIS/GPS with stroke delimber and grapple skidder.

To assess the productivity and unit cost of a de-coupled grapple skidder and stroke delimber system we used the total productive time spent skidding and delimbing of our base scenario (Scenario 1), respectively. We then divided the total wood volume by the time for each machine to estimate machine productivity. Unit cost of production for each machine was calculated using the same machine rates as mentioned before. To estimate the unit cost of the system we added the unit cost of the two machines together.

RESULTS

Stroke Delimber Percent Idle Time

Stroke delimber percent idle times ranged from 0% to 79% across all four scenarios tested in our model (Figure 2.3). A great variation in stroke delimber percent idle time could be found between the individual scenarios and changes in bunch size, as represented by changes in bunch spacing and removal intensity (Figure 2.3). There were no significant differences ($p>0.092$) in percent idle time between Scenarios 1 and 2 for bunch spacings of 11 m or removal intensities of 67 tonnes/ha. For bunch spacings of 18 and 25 m and removal intensities of 112 and 157 tonnes/ha there were significant differences ($p<0.001$) between the two scenarios. Stroke delimber percent idle time in Scenario 3, when the delimbing process is sped up by one second per tree, is generally higher than the percent idle time in Scenario 1 or 2. Two exceptions occurred when the bunch spacing was 18 or 25 m and the removal intensity was 157 tonnes/ha (Figure 2.3). The percent idle time in Scenario 4 was always less than for any other scenario.

The results clearly show that there is no significant difference in stroke delimber percent idle time between clearing the main trail first (Scenario 1) and achieving the lowest stroke delimber idle time possible (Scenario 2) for short bunch spacings and low removal intensities. At larger bunch spacings and higher removal intensities the difference can mostly be seen at short skidding distances and the effect gets smaller with longer skidding distances. The results also clearly show that speeding up the processing times for individual trees (Scenario 3) results in a higher percent idle time than observed in Scenarios 1 or 2. Using two skidders (Scenario 4), however, clearly reduced the percent idle time of a stroke delimber by up to two thirds.

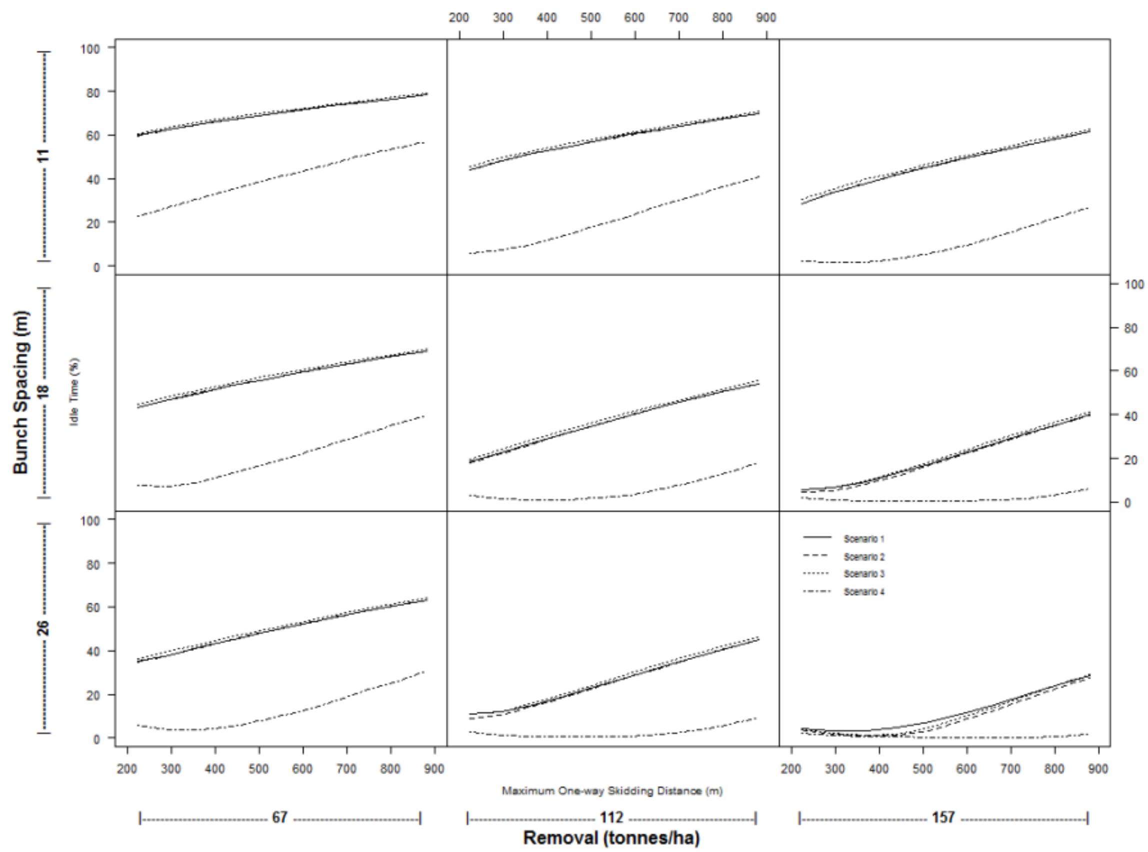

Figure 2.3: Stroke delimber idle time for four different model scenarios, various maximum one-way skidding distances, and different bunch spacings and removal intensities. Scenario 1 is the base scenario with one grapple skidder and one stroke delimber where the main trail is cleared first. Scenario 2 implements the use of GIS/GPS to reduce the waiting time of the stroke delimber to a minimum. Scenario 3 uses the same technology as Scenario 2 but introduces best processing practices that lead to a decrease in stroke delimber processing time by one second per tree. Scenario 4 uses two skidders and one stroke delimber.

Grapple Skidder Idle Time

Grapple skidder percent idle times ranged from 0% to 63% across all four scenarios tested in our model (Figure 2.4). No statistical difference ($p>0.457$) was found between grapple skidder percent idle time for Scenarios 1 and 2 at a bunch spacing of 11 m and removal intensities of 67 and 112 tonnes/ha. Grapple skidder percent idle time in Scenario 4 increased with increasing bunch spacing and removal intensity but decreased with increasing skidding distance (Figure 2.4). A similar effect was seen in the other three scenarios with a smaller effect on percent idle time. The most distinct differences ($p<0.001$) between all four scenarios could be found at a bunch spacing of 25 m and a removal intensity of 157 tonnes/ha. Scenarios 1 and 4 had the highest percent idle times, while Scenarios 2 and 3 resulted in the lowest (Figure 2.4).

System Productivity

System productivity ranged from 6.0 tonnes/PMH to 43.4 tonnes/PMH across all four scenarios tested in our model (Figure 2.5). The results showed that there is no difference ($p>0.240$) in system productivity between Scenarios 1, 2 and 3 at a bunch spacing of 11 m and a removal intensities of 112 tonnes/ha. Other combinations of bunch spacing and removal intensities between the four scenarios resulted in significant differences ($p<0.010$). The results clearly show that Scenario 4 had the highest productivity. However, at large bunch spacings, high removal intensities, and short skidding distances the differences were minimal. The productivity in Scenario 3 was higher than for Scenario 2 which was higher than the productivity in Scenario 1.

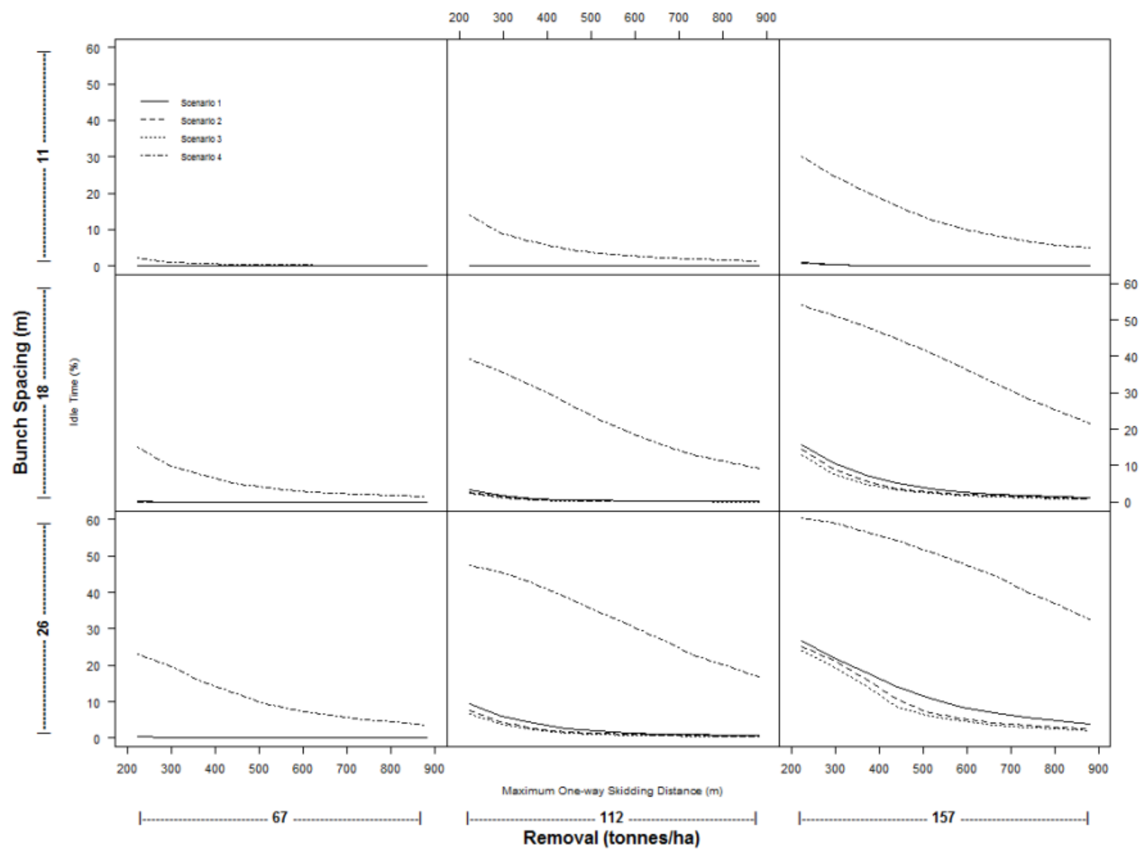

Figure 2.4: Grapple skidder percent idle time for four different model scenarios, various maximum one-way skidding distances, and different bunch spacings and removal intensities. Scenario 1 is the base scenario with one grapple skidder and one stroke delimber where the main trail is cleared first. Scenario 2 implements the use of GIS/GPS to reduce the waiting time of the stroke delimber to a minimum. Scenario 3 uses the same technology as Scenario 2 but introduces best processing practices that lead to a decrease in stroke delimber processing time by one second per tree. Scenario 4 uses two skidders and one stroke delimber.

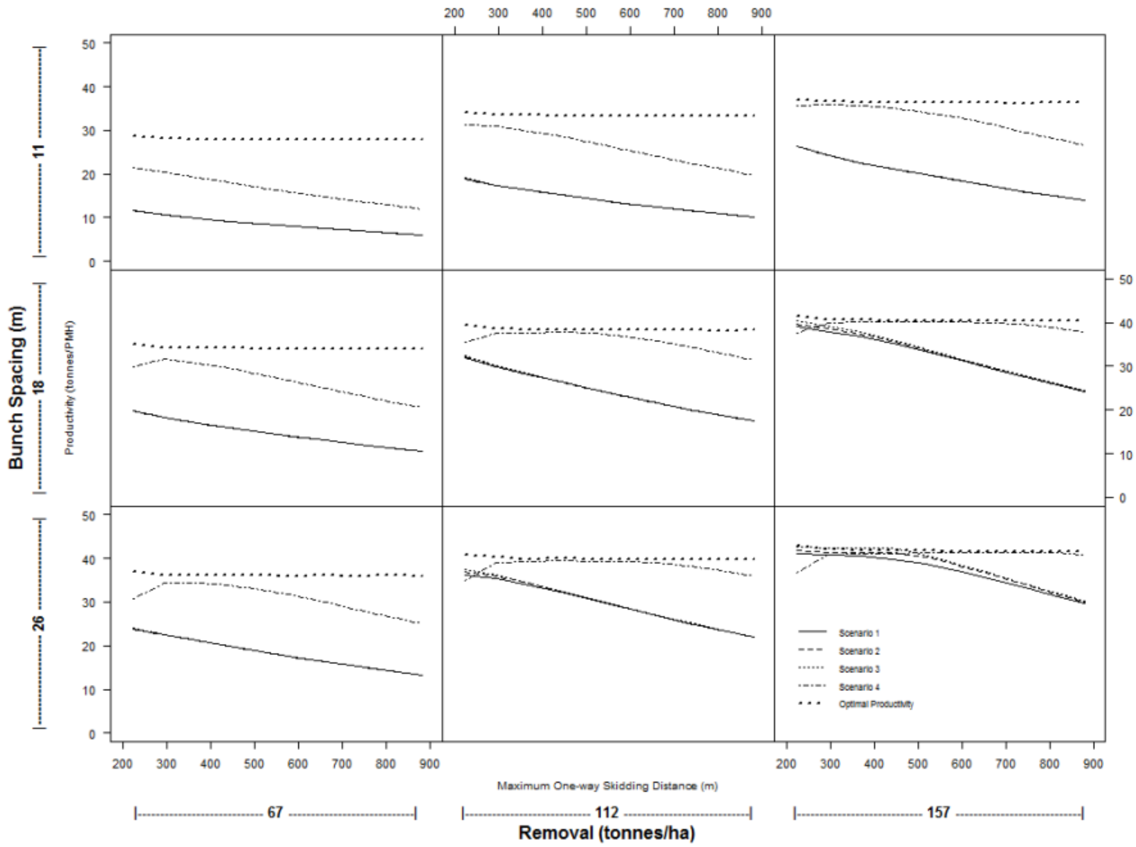

Figure 2.5: System productivity for four different model scenarios, various maximum one-way skidding distances, and different bunch spacings and removal intensities. Optimal system productivity is shown based on a de-coupled system. Scenario 1 is the base scenario with one grapple skidder and one stroke delimber where the main trail is cleared first. Scenario 2 implements the use of GIS/GPS to reduce the waiting time of the stroke delimber to a minimum. Scenario 3 uses the same technology as Scenario 2 but introduces best processing practices that lead to a decrease in stroke delimber processing time by one second per tree. Scenario 4 uses two skidders and one stroke delimber.

Further, the results clearly show that the stroke delimber could achieve high productivities when there is no need to wait for a grapple skidder (e.g. a de-coupled system). Productivity remained constant across a range of skidding distances, but increased with an increase in bunch size, as is represented by an increase in bunch spacing and removal intensity (Figure 2.5). In all cases the optimal system productivity of a de-coupled system was higher than the productivity of any other scenario. However, at large bunch spacings and high removal intensities all four scenarios tested were approaching optimal productivity levels.

Unit Cost of Production

The unit cost of production for grapple skidder and stroke delimber combined ranged from 5.30 $/tonne to 38.36 $/tonne across all four scenarios tested in our model (Figure 2.6). The unit cost increased with increasing skidding distance for all behaviors tested, but decreased with increasing bunch size, as is represented by increasing bunch spacing and removal intensity. At large bunch spacings and high removal intensities, however, the unit cost of Scenario 4 decreased with increasing skidding distance. Scenario 4 was consistently different from the other three scenarios ($p<0.001$). No differences were found between Scenario 1 and Scenario 2 at a bunch spacing of 11 m ($p>0.137$) and a removal intensity of 112 tonnes/ha ($p=0.735$). Similar differences and similarities were found between the unit cost of Scenario 1 and Scenario 3, and Scenario 2 and Scenario 3. Results clearly show that using two skidders (Scenario 4) lowers the unit cost when skidding small bunches but increases the unit cost when skidding large bunches, especially at short skidding distances.

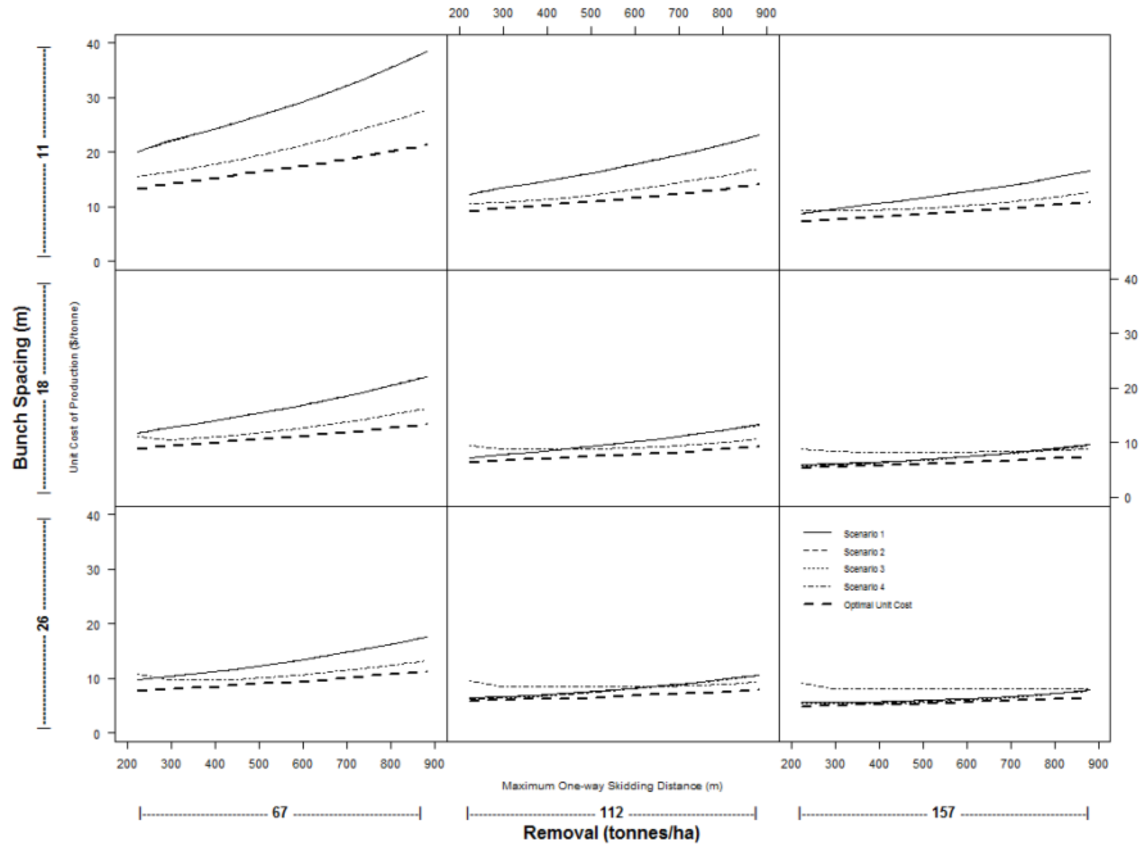

Figure 2.6: Unit cost of productivity for four different model scenarios, various maximum one-way skidding distances, and different bunch spacings and removal intensities. Scenario 1 is the base scenario with one grapple skidder and one stroke delimber where the main trail is cleared first. Scenario 2 implements the use of GIS/GPS to reduce the waiting time of the stroke delimber to a minimum. Scenario 3 uses the same technology as Scenario 2 but introduces best processing practices that lead to a decrease in stroke delimber processing time by one second per tree. Scenario 4 uses two skidders and one stroke delimber.

Optimal system unit cost of the de-coupled system increased with increasing skidding distance and decreased with increasing bunch spacing and removal intensity (Figure 2.6). Optimal system unit cost differences compared to the baseline unit cost (Scenario 1) were smaller at short skidding distances but increased with increasing skidding distance. Differences also decreased with increasing bunch spacing and removal intensity. At large bunch spacings and high removal intensities the unit cost of Scenarios 1 to 3 were approaching the optimal unit cost, while the unit cost of Scenario 4 was higher than any of the other unit costs.

Cost Savings by using GPS/GIS Technology

Based on average skidding and delimbing conditions in Maine our results showed that the average system unit cost for Scenario 2 was significantly lower ($p<0.001$) than the unit cost of Scenario 1 with a difference of 0.18%. This amounts to a saving of 0.015 $/tonne. Multiplying this cost saving by an average annual production of 9,000 tonnes resulted in annual saving of $135, when using a GIS/GPS based communications system and assuming a perfect flow of information.

DISCUSSION

Computer simulations are well respected tools in forestry and have been available since the 1960's (Polley 1987; Goulet et al. 1979). Conducting operations specific time and motion studies to answer the question of whether or not a change in harvesting behavior would result in a change of productivity, unit cost, or individual machine idle time, is time consuming and expensive. The model developed in Chapter 1 was developed to specifically answer this question without changing the real system and ensuring a fast execution. The results presented in this paper clearly show that changes in operational behavior can have an impact on the variables of interest mentioned before. However, the results also show that the differences are partial to initial operational conditions such as skidding distance, bunch spacing, and removal intensity. Bunch spacing and removal intensity are variables that subsequently control bunch size.

Stroke delimber percent idle time is mostly influenced by the use of two grapple skidders and a decreased processing time per tree. The use of two grapple skidders in Maine is not uncommon and has been observed during the data collection period of a study by Hiesl (2013). The major reason for a significant drop in percent idle time when using two grapple skidders is the fact that the wood flow to the landing is increased and the stroke delimber is less likely to be waiting for a bunch of wood that can be processed. Our results clearly show that the stroke delimber percent idle time, the time the machine is waiting for the grapple skidder to deliver a bunch of wood to the landing, can be close to 80%, depending on the initial site conditions. A decrease in percent idle time with an increase in bunch size is not surprising. A larger bunch size is associated with more trees that need to be processed, which increase the time needed to process a bunch. Further, a larger bunch size might also include trees with a larger diameter. Tree diameter has been shown to affect stroke delimber cycle time in Maine (Hiesl 2013; Hiesl and Benjamin 2013c).

For the grapple skidder the percent idle time is mostly influenced by large bunch sizes. However, this effect is negated with increasing skidding distance. The reason for this is that a large bunch size increases the processing time of the stroke delimber. The grapple skidder and stroke delimber systems in Maine commonly operate on small landings where only one bunch can be placed in front of the delimber at any given time. With an increased processing time for the stroke delimber this means that the grapple skidder has to wait before the next bunch can be dropped. With longer skidding distances the skidding time increases (Hiesl and Benjamin 2013c; Kluender et al. 1997), and therefore the waiting time at the landing decreases. Even though results showed that the use of two grapple skidders (Scenario 4) significantly decreased stroke delimber percent idle time, it also increased grapple skidder percent idle time. This increase was most prominent at large bunch sizes, which can be attributed to the fact that stroke delimber waiting time at large bunch sizes is already minimal. This is especially true at short skidding distances.

The biggest impact, however, on stroke delimber and grapple skidder percent idle time is the coupled nature of these machines (Polley 1987). A coupled system consists of two or more machines that are dependent on each other in terms of production (Polley 1987). In this case the stroke delimber is dependent on the grapple skidder as the machine has to wait for bunches of wood to be delivered to the landing by the grapple skidder. This negative impact of a coupled system has been reported by Polley (1987) with the suggestion that this system needs to be decoupled in the future. De-coupling of this system would clearly result in zero idle time for either machine. The de-coupled operation of these machines was a common picture in Maine in the past (personal communication with several foresters, October, 2013). During that time, individual bunches were placed along the roadside and stacked on top of each other. The stroke delimber would start processing trees from one end and work its way through the pile of trees. This way, neither machine was immediately dependent on the other. The downside of this system was that a large area along the road was used as a landing and therefore temporarily taken out of production (personal communication with several foresters, October, 2013). Around 1990, landownership in northern Maine was changing

(Jin and Sader 2006) and it is likely that this change in ownership prohibited the piling of wood along roads to preserve the standing timber along the road in a productive stand.

The analysis of machine productivity of such a de-coupled system showed that stroke delimber productivity stayed reasonably constant, regardless of skidding distance, as was to be expected. Reason for the variation in stroke delimber productivity is the stochasticity of tree diameter selection in the model (see Chapter 1). Stroke delimber productivity increases with an increase in bunch spacing and removal intensity. This increase in productivity can be attributed to stochasticity of the model as well, as a larger removal intensity leads the model to increase the number, diameter, and volume of individual trees in each bunch, which subsequently affect productivity. Grapple skidder productivity, however, is strongly affected by skidding distance, as has been shown in several research studies (e.g. Hiesl and Benjamin 2013; Kluender et al. 1997). In addition to skidding distance, bunch size is also known to affect grapple skidder productivity (Hiesl 2013; Hiesl and Benjamin 2013c). This effect can be seen by the increase in grapple skidder productivity with increasing bunch spacing and removal intensity. The use of two grapple skidders increased system productivity the most across the full range of bunch spacings and removal intensities tested. The reason for this is the reduction in stroke delimber percent idle time. Due to this reduction in percent idle time more wood is being processed in the same amount of time which subsequently leads to an increase in system productivity. However, at wider bunch spacings and high removal intensities the productivity of the other three scenarios tested is almost as high that the productivity of a system using two grapple skidders, at least at short skidding distances. Productivity barely increases from the baseline (Scenario 1) when looking at any of the other two scenarios. A larger increase in productivity, however, can be seen at higher removal intensities and wider bunch spacings. As before, the reduction in stroke delimber percent idle time, associated with Scenario 2 and 3, is the major driver in this increase in productivity.

Clearly, at the end of the day the unit cost of production is the variable of interest in judging whether or not a change in operating behavior is economically desirable. It is not surprising to see that the unit cost is decreasing with increasing bunch size. Unit cost is a function of machine rate and productivity, and it has already been proven that bunch size affects grapple skidder productivity (Hiesl 2013; Hiesl and Benjamin 2013c). The use of two grapple skidders results in a much lower unit cost, especially when the bunch size is small. With larger bunch sizes the difference in unit costs between using two or one skidder(s) decreases and even reverses. Reason for this is that with larger bunch sizes the stroke delimber percent idle time of a system consisting of one grapple skidder and one stroke delimber is so low that the use of two grapple skidders cannot lower this percent idle time as much as it can when operating with small bunch sizes. Due to this, at wider bunch spacings and higher removal intensities, grapple skidder percent idle time increases and therefore causes higher costs. Looking at the combined unit cost of stroke delimber and grapple skidder, when they operate as a de-coupled system, clearly showed that the optimal unit cost could be over 40% lower than the system unit cost of Scenario 1, when dealing with small bunch sizes and long skidding distances. This difference, however, decreases with an increase in bunch size, which can be attributed to the low percent idle time for either machine in these instances.

The major limitation of this analysis is that we only looked into skidding and delimbing scenarios that consisted of 50% hardwood content. It has been shown that stroke delimber cycle time (the processing time of one tree), is lower for softwood than hardwood species (Hiesl 2013; Hiesl and Benjamin 2013c). This means that in a stand consisting of softwood species only, the stroke delimber productivity will be higher than the productivity in a mixed-wood stand, as used in this simulation. The model developed in Chapter 1 is clearly capable of simulating an increase or decrease in hardwood content and therefore change the results in terms of idle time, productivity, and unit cost. An analysis of these scenarios might be more useful to individual land managers and logging contractors to determine whether or not an investment in new technology or a second grapple skidder would be worth the investment for their average operating conditions.

CONCLUSION

Whether or not to invest in new technology is a question that many logging contractors face in recent time. Our analysis showed that an investment in GPS/GIS technology minimally decreases the unit cost of production. However, with small profit margins this decrease in unit cost might make the difference between making a profit or loss. Whether or not this decrease in unit cost is worth an investment in new technology depends on the cost of this new technology but also on the annual production. The more surprising results, however, were the high productivity and low unit cost of a system working with two grapple skidders across most skidding distances and bunch sizes simulated. The results clearly indicate that using such a system could significantly increase the throughput of a system and subsequently profit, especially when operating with small bunch sizes. Even though such a system shows all these benefits, it is not as commonly used in Maine as one would expect. Clearly there is room for improvement in Maine’s forest operations, and investing in a second grapple skidder might be just one. Using this information as a base scenario, the next step in research could be to evaluate the effects new technology could have in such a system.

In the best case, stroke delimber or grapple skidder percent idle time is approximately 5%, when skidding bunches of large sizes. The large bunch sizes necessary to achieve such a low percent idle time, however, are not common in Maine. De-coupling the system of grapple skidder and stroke delimber would eliminate any waiting time and also increase productivity and decrease unit cost. However, to assess whether or not these machines can be de-coupled in an industry setting, it is necessary to gather more information about the loss of stand production when piling bunches along the road, and whether or not this method would work with today's landownership pattern.

CHAPTER THREE:

EVALUATING HARVEST COSTS AND PROFIT OF COMMERCIAL THINNINGS IN SOFTWOOD STANDS IN WEST-CENTRAL MAINE: A CASE STUDY[1]

ABSTRACT

Precommercial thinning (PCT) is a common silvicultural treatment in the management of young conifer forests. The positive effects of PCT on tree growth are well documented, however, there have been few operational studies of thinning productivity associated with later harvests in such stands and associated cost comparison with high-density, small-diameter stands. In the winters of 2012/2013 and 2013/2014 a long-term herbicide and PCT study in west-central Maine was commercially thinned using cut-to-length (CTL) and whole-tree (WT) harvesting systems in PCT and non-PCT stands, respectively. Thinning prescriptions consisted of three nominal removal intensities (33 %, 50 %, and 66 % of the standing softwood volume) in a randomized block design with three to four replications. Stand density, basal area, hardwood content, and removal intensity were not significant in explaining variation in harvester and feller-buncher productivity. An analysis of unit cost of production indicated that wood chip production using a WT system in non-PCT stands is less costly than the production of roundwood using a CTL system in PCT stands. Profit, however, is similar for products harvested by either system. Our conclusion is that the WT system used in the study is economically feasible to treat high-density, small-diameter stands in a commercial thinning.

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[1] Hiesl, P., J.G. Benjamin, and B.E. Roth. 2015. Evaluating harvest costs and profits of commercial thinnings in softwood stands in west-central Maine: A case study. The Forestry Chronicle, 91 (2), pp. 150-160.

INTRODUCTION

Precommercial thinning (PCT) is a common silvicultural treatment used in the early management of conifer forests across North America and Europe (Bataineh et al. 2013; Olson et al. 2012; Zhang et al. 2006). The effects of PCT on tree growth have been investigated and documented for a wide range of forest types (Bataineh et al. 2013; Olson et al. 2012; Pitt and Lanteigne 2008; Zhang et al. 2006; Brissette et al. 1999; Balmer et al. 1978), however, this treatment represents a significant financial investment by the landowner which must be carried many years before a commercial harvest. Long-term results of growth responses and financial returns by PCT treatments are limited in the Acadian forest region (Bataineh et al. 2013; Pitt et al. 2013b; Saunders et al. 2008). Results from a 40-year spruce-fir (*Picea rubens* Sarg., *Abies balsamea* (L.) Mill.) study in west-central Maine involving a combination of early herbicide and PCT show that 13 to 24 years following PCT, the diameter and height increment was greater than that for non-PCT trees (Bataineh et al. 2013). The authors further reported that the total stumpage value of PCT stands was on average USD $907/ha higher than for non-PCT stands of the same age. A long-term PCT study from New Brunswick, Canada found that PCT increased diameter growth rates with responses proportional to the thinning intensity (Pitt et al. 2013a). Half the plots were clear-cut in 2008 at ages 55 and 62, and results showed that harvester productivity increased in proportion to PCT intensity due to the positive effect of PCT on average stem size (Plamondon and Pitt 2013). Another benefit of PCT is that it can increase regeneration and thus function similar to a shelterwood establishment cut (Olson et al. 2014). This study was conducted in Maine and shows that the abundance of medium (0.61–1.40 m tall) and large (≥1.41 m tall to 9.90 cm dbh) softwoods increased with increasing thinning intensity.

Typically, a commercial thinning (CT) is prescribed many years after PCT to further improve residual stand conditions and stand growth and yield (Pekol et al. 2012; Smith 1986). Clune (2013) studied spruce-fir response to a combination of commercial thinning methods, timings and intensities of removal over the past decade in Maine, with results showing the benefit of CT on stand stability and growth. CT has been shown to focus diameter and volume growth on a selected number of stems and therefore decreases the growing time to a specific merchantable volume (Pelletier and Pitt 2008).

Maine consists of millions of acres of small-diameter forest land (McCaskill et al. 2011) that either are in need of PCT or have already passed the right time for an economical treatment. One of the challenges regarding such stands is to determine how they can be operationally treated in a cost-effective manner to increase growth and yield of individual trees. During the winters of 2012/2013 and 2013/2014, the long-term Austin Pond study in west-central Maine (Newton et al. 1992a; Newton et al. 1992b), which began as a herbicide screening trial and was later expanded into a long-term PCT study, received a first-entry commercial thinning. Two stand conditions were harvested: (1) a 42-year-old stand that received PCT at age 16 and, (2) a 43-year-old stand that did not receive a PCT treatment. Three different thinning intensities were prescribed with three to four replicates (non-PCT and PCT respectively) in a randomized block design. Harvest systems were matched to stand conditions with a cut-to-length system assigned to harvest PCT stands and a whole-tree system assigned to non-PCT stands. The harvest systems chosen are currently operational in Maine and represent one possible combination of equipment to conduct a CT in the described stands. Our first objective was to compare productivity of harvester and feller-buncher operating with three different removal intensities. The second objective was to compare the harvest costs and profit of CT in PCT and non-PCT stands to assess the economic feasibility of such a treatment.

METHODS

Site

Detailed information about the Austin Pond study site are described in the publications of Newton *et al.* 1992a, 1992b; Bataineh *et al*. 2013. The study site is located in Somerset County, Maine (45.20°N, 69.70°W). Mean annual precipitation is 100 cm with 40 % occurring from June through September. The site was clear-cut in 1970 and an herbicide screening trial designed to release naturally regenerated conifers from competing hardwoods was installed seven years later. Sixteen years after the harvest, each herbicide treatment unit (approximately 1 ha) was split, with one half pre-commercially thinned to approximately 1730 trees/ha. In 2012, 21 measurement plots (809 m^2) were installed in a subset of the original herbicide x PCT treatment units. Species, diameter at breast height (dbh), total height, and height to the base of the live crown were recorded for all trees >7.6 cm in dbh. Mean dbh for PCT stands ranged from 13.1 cm to 18.7 cm with stand densities ranging from 1309 to 2594 trees/ha (Table 3.1). For non-PCT stands, mean dbh ranged from 9.6 cm to 12.8 cm with stand densities ranging from 3211 to 5496 trees/ha (Table 3.1). Based on the number of stems, all stands were dominated by balsam fir (*Abies balsamea* (L.) Mill.) and consisted of 4 % and 28 % red spruce (*Picea rubens* Sarg.), 1 % to 30 % quaking aspen (*Populus tremuloides* Michx.), and up to 35 % of other species such as paper birch (*Betula papyrifera* Marshall), yellow birch (*Betula alleghaniensis* Britt.), eastern white pine (*Pinus strobus* L.), and northern white cedar (*Thuja occidentalis* L.). Individual treatment units ranged in size from 0.40 to 0.71 ha (Table 3.1).

Table 3.1: Individual tree and stand attributes for PCT and non-PCT harvest treatments

Plot	Block	Treatment unit (ha)	Mean dbh (cm)	Mean height (m)	Mean height to crown (m)	Stand density (trees/ha)	Basal area (m^2/ha)	Piece size (m^3)	Hardwood component (%)
PCT Treatments									
1T	T1	0.57	13.7	12.8	7.2	2334	37.7	0.08	35
3T	T2	0.61	15.6	12.3	6.2	1778	36.7	0.11	3
4T	T3	0.49	13.1	11.7	6.4	2470	36.8	0.07	22
7T	T2	0.61	13.9	11.3	4.5	1581	26.0	0.08	9
10T	T2	0.45	18.7	13.5	6.4	1309	37.6	0.17	0
11T	T4	0.53	14.1	10.8	4.2	1618	27.3	0.08	1
12T	T1	0.40	12.5	12.1	6.2	2495	33.5	0.06	32
15T	T4	0.49	14.0	12.8	6.9	2198	37.1	0.09	23
17T	T4	0.49	15.2	13.4	7.3	2062	41.4	0.12	16
21T	T3	0.61	13.4	12.1	6.5	2594	41.4	0.08	24
23T	T3	0.45	14.2	12.7	6.8	2297	40.6	0.09	16
27T	T1	0.57	15.4	13.1	7.1	1976	42.0	0.13	18
Non-PCT Treatments									
2U	U1	0.49	10.6	11.2	7.2	4162	40.7	0.04	21
4U	U1	0.40	10.5	11.2	6.5	4211	41.5	0.04	27
10U	U3	0.49	11.0	11.2	6.7	3668	39.2	0.05	23
13U	U2	0.61	9.8	10.4	6.4	5496	45.6	0.03	14
16U	U3	0.57	12.8	13.0	8.5	3211	47.6	0.08	7
18U	U2	0.65	9.6	10.2	6	5372	42.8	0.03	10
22U	U2	0.71	10.2	10.9	7.2	5483	49.8	0.04	2
24U	U3	0.53	11.1	11.3	7.2	3507	38.6	0.04	37
27U	U1	0.49	10.9	11	6.4	3668	38.7	0.04	15

Experimental Design

Three different thinning prescriptions were implemented with three to four replicates across non-PCT and PCT-treated stands (Table 3.2). Nominal thinning prescriptions were to remove 33 %, 50 %, or 66 % of the standing softwood volume using a modified thinning from below prescription, which included the removal of large balsam fir (dbh > 20 cm) to ensure utilization of such trees before butt rot will decrease their value (Tian 2002; Seymour 1995). To achieve this goal, a computer program developed by the Cooperative Forestry Research Unit at the University of Maine was used to mark individual trees in the field. The program used regional volume equations to accurately calculate the total volume removed as trees are marked for removal to reach the target removal % for each plot.

Table 3.2: Nominal description of three prescriptions across PCT and non-PCT stands. The prescription was marked without the inclusion of trails. Due to this exclusion the effective removal is larger than the prescription indicates. The three prescriptions consist of a thinning from below with the addition of removing large balsam fir (dbh > 20 cm).

Prescription	Description
33%	Removal of 33% of softwood volume, with 100% removal of hardwoods. Softwoods are to be thinned to 3.0 m to 4.6 m spacing for PCT stands and 2.4 m to 3.0 m spacing for non-PCT stands. Priority for retention: RS > WP > WC > BF
50%	Removal of 50% of softwood volume, with 100% removal of hardwoods. Softwoods are to be thinned to 3.0 m to 4.6 m spacing for PCT stands and 2.4 m to 3.0 m spacing for non-PCT stand. Priority for retention: RS > WP > WC >BF
66%	Removal of 66% of softwood volume, with 100% removal of hardwoods. Softwoods are to be thinned to 3.0 m to 4.6 m spacing for PCT stands and 2.4 m to 3.0 m spacing for non-PCT stands. Priority for retention: RS > WP > WC > BF

Note: RS = red spruce, WP = eastern white pine, WC = northern white cedar, BF = balsam fir

The blocking of individual treatment units with one of the three prescriptions was based on relative stand density (RD) and the quadratic mean diameter (QD). An analysis of stand information showed that several groups with similar RD and QD values existed. In each of these groups the prescriptions were randomly assigned. This approach ensured that each prescription was implemented across a variety of RD and QD conditions.

As the Austin Pond study is predominantly a softwood research project, the prescription further included the removal of all hardwood trees unless they would fill a gap in the stand. All crop trees were marked before the thinning, and harvest trails were overlaid using a trail spacing of 15.2 m (centre of trail to centre of trail). Therefore as a result, the effective total removal of softwood volume is greater than the nominal prescription indicates.

The nominal thinning prescriptions resulted in basal area removals of 33 % to 75 %, and 57 % to 80 % in PCT and non-PCT stands, respectively. Prescriptions for thinnings in excess of 50 % of the basal area are not common in this region, however, such high removal intensities increase the amount of softwood regeneration (Olson et al. 2014). The highest removal intensities therefore represent an extreme entry that will be used to gain information about stand responses to such a treatment in future research projects.

Equipment Selection

PCT treatment units were thinned using a cut-to-length harvesting system consisting of a Ponsse Ergo harvester and a Timberjack 1110 forwarder. This system was chosen for its efficiency in thinning operations, the narrow trail width necessary, and availability of the contractor at the time of harvest. Non-PCT treatment units were thinned using a whole-tree harvesting system consisting of a CAT 501 feller-buncher and a John Deere 648 GIII grapple skidder. The CAT 501 feller-buncher was chosen for its narrow track width and small machine size. Although this machine is not widely used in Maine, its productivity data in similar high density stands showed a great potential for economically feasible thinnings (Benjamin et al. 2013). Unpublished data from research conducted by Benjamin *et al*. (2013) and Hiesl (2013) in this region further showed that cut-to-length systems commonly used in Maine were not cost efficient in thinning high density small diameter softwood stands such as the non-PCT stands in this study. A truck mounted Prentiss 325 loader was used to load roundwood trucks and to feed a Morbark Model 23 disk chipper.

Equipment operators in this study had between seven and thirty years of experience working in similar stand conditions. Experienced operators were chosen to minimize residual stand damage and to ensure high harvest productivity, as the operator can have a large effect on machine productivity (Hiesl 2013; Hiesl and Benjamin 2013a; Purfürst and Erler 2011; Kärhä et al. 2004).

Measurements

Twelve PCT and nine non-PCT treatment units were thinned by the harvester and feller-buncher, respectively. During active operations, machine operators were required to maintain a record of harvesting time for each treatment unit including delays less than 15 minutes. Due to the randomized harvest design, up to three treatment units were situated in one row with trails running their length (Figure 3.1). As the travel time from one trail to another trail would be greater for the second and third unit in a row, the machine operators were asked to only record the productive time from the harvest unit boundary onwards. This ensured that only times that were associated with the immediate thinning were recorded and analyzed. Wood extraction time (e.g., forwarder and skidder) was modelled using regional cycle time equations (Hiesl 2013; Hiesl and Benjamin 2013c).

Three different products were processed by the harvester: spruce/fir pulpwood (3.6 m), spruce/fir saw logs in three lengths (3.6 m, 4.3 m, 4.9 m), and tree-length hardwood pulpwood. To ensure accurate measurements of the harvested volume, we asked the forwarder and skidder operators to separate each product at the landing by harvest plot. Individual log and whole-tree piles were painted with the plot number for later reference.

These piles were measured (width x length x height) at the landing for plot-level volume before being trucked to the mill. The plot-level fractions of total wood harvested were later multiplied by the mill-delivered total to estimate mill-scaled removals from each harvest unit. This approach was deemed to be more efficient than weighing a sub-sample of each plot in the field based on results from Benjamin *et al.* (2013). All roundwood was transported and scaled within two days of harvest. Total weight measured in short tons, as determined from mill scales, was converted to metric tonnes using a conversion factor of 0.907 tonnes: ton. Productivity (tonnes/PMH) for the harvester and feller-buncher per treatment unit was then calculated (Table 3.3).

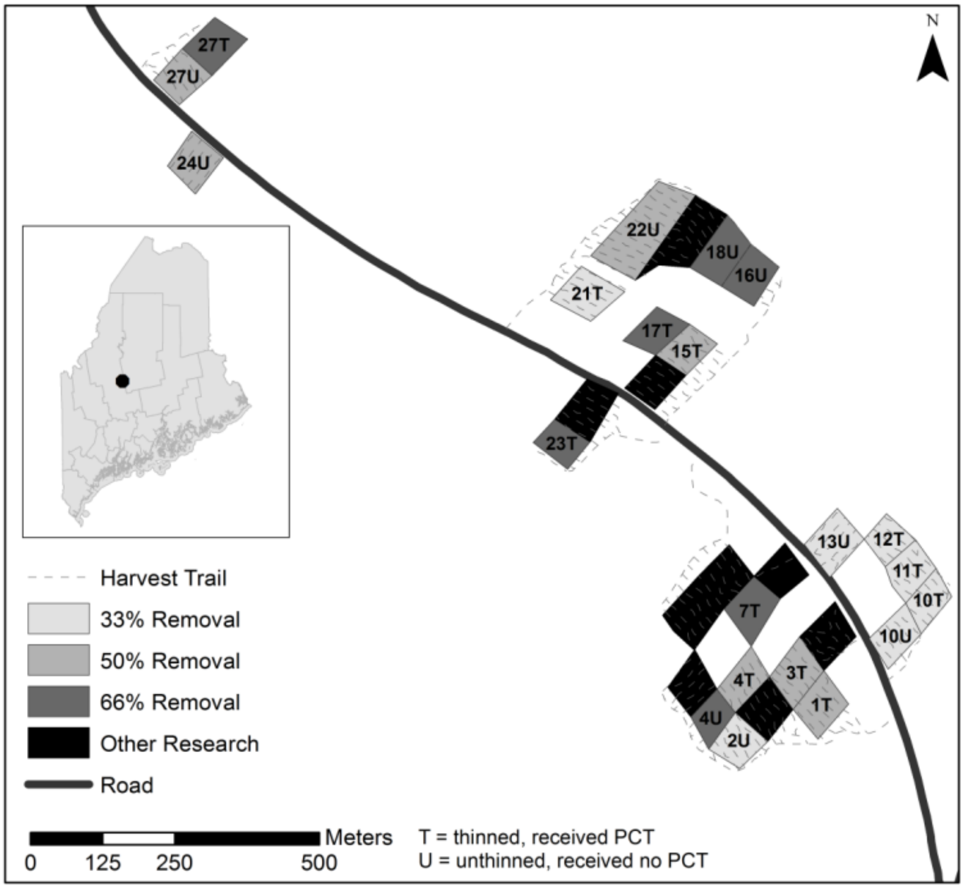

Figure 3.1: Map of Austin Pond harvest layout for PCT and non-PCT treatment units in Somerset County, Maine (45.20°N, 69.70°W). Three prescriptions were applied to PCT and non-PCT treatment units. Plot numbers followed by a 'T' received a PCT treatment in 1986 while those followed by a 'U' did not. PCT stands were harvested in 2013 with a cut-to-length system while non-PCT plots were harvested with a whole-tree system.

Table 3.3: Harvest information for PCT and non-PCT stands by thinning treatment.

Plot	Block	Machine type	Treatment unit (ha)	Prescription (%)*	Basal area removed (%)	Harvest time (min)	Removal (tonnes)	Productivity (tonnes/PMH)
PCT Treatments								
1T	T1	Harvester	0.57	50	63	468	47.5	6.1
3T	T2	Harvester	0.61	50	51	290	41.3	8.5
4T	T3	Harvester	0.49	50	57	375	39.4	6.3
7T	T2	Harvester	0.61	66	64	370	45.5	7.4
10T	T2	Harvester	0.45	33	42	117	39.6	20.3
11T	T4	Harvester	0.53	33	33	160	24.9	9.3
12T	T1	Harvester	0.40	33	49	185	25.8	8.4
15T	T4	Harvester	0.49	50	61	313	56.1	10.8
17T	T4	Harvester	0.49	66	71	370	51.2	8.3
21T	T3	Harvester	0.61	33	48	427	35.0	4.9
23T	T3	Harvester	0.45	66	75	356	37.2	6.3
27T	T1	Harvester	0.57	66	63	361	50.6	8.4
Non-PCT Treatments								
2U	U1	Feller-buncher	0.49	33	57	293	99.6	20.4
4U	U1	Feller-buncher	0.40	66	77	330	58.1	10.6
10U	U3	Feller-buncher	0.49	33	62	334	58.2	10.5
13U	U2	Feller-buncher	0.61	33	63	626	74.5	7.1
16U	U3	Feller-buncher	0.57	66	80	509	90.2	10.6
18U	U2	Feller-buncher	0.65	66	79	542	125.4	13.9
22U	U2	Feller-buncher	0.71	50	68	509	125.7	14.8
24U	U3	Feller-buncher	0.53	50	68	448	94.1	12.6
27U	U1	Feller-buncher	0.49	50	69	285	66.9	14.1

*Removal of standing softwood volume.

Unit Cost of Production

Hourly machine costs were developed using the approach outlined by Brinker *et al.* (2002). The machine rates used in this paper refer to the costs to own and operate a piece of equipment, however they do not include other business related expenses (e.g. moving of equipment, service trucks, administration). Machine rates for the Ponsse Ergo harvester, CAT 501 feller-buncher, Timberjack 1110 forwarder, and John Deere 648 GIII grapple skidder were adapted from unpublished data of an early commercial thinning study by Benjamin *et al.* (2013). Loader and chipper rates were supplied by an anonymous source and are representative of regional rates between 2011 and 2014 (Table 3.4). The total unit cost of production includes the costs of wood products from stump to mill.

Table 3.4: Hourly machine rates used in this analysis. Common hourly rates are represented by the range of values.

Machine	Machine type	Hourly rate (USD \$ PMH^{-1})
Ponsse Ergo	Harvester	121–161
Timberjack 1110	Forwarder	92–119
CAT 501	Feller-Buncher	103–135
John Deere 648 GIII	Grapple Skidder	90–115
Prentiss 325	Loader	40
Morbark Model 23	Chipper	62–94

Unit cost calculations for the harvester and feller-buncher were based on the productivity measured in each harvest unit. As the forwarding and skidding times were not measured, we used regional cycle time equations (Hiesl 2013; Hiesl and Benjamin

2013c) to estimate extraction times. In this analysis, we assumed that each harvest unit consisted of five trails with a maximum distance to the landing of 210 m, 240 m, 250 m, 270 m, and 280 m. For each trail, 75 m were within the harvest unit while the remaining distance was from the landing to the beginning of the harvest unit. These assumptions ensured the accurate comparison of thinning productivity and costs between the individual treatments.

The number of loads per treatment unit for the forwarder was calculated based on the harvested volume. For this calculation we used the average piece size of each unit (Table 3.1). A forwarder load consisted of 150 or fewer logs. For the grapple skidder, the number of twitches/treatment unit was calculated based on the harvest volume using an average twitch size of 3.0 tonnes. We assumed that the twitches were evenly distributed along the trails within the treatment unit. Time accumulated was multiplied by the hourly rate for each machine to calculate the total extraction costs per treatment unit.

Trucking costs to the mill in this region are USD $1.67/km (Benjamin 2014). Roundwood is generally transported in a wider radius than wood chips and therefore we assumed a round-trip distance of between 80 and 160 km for roundwood and 50 to 100 km for wood chips. The average load per truck was 35.1 tonnes for roundwood and 24.2 tonnes for wood chips. Based on personal communications with various logging contractors the average loading times for roundwood and wood chips were assumed to be 25 minutes and 35 minutes, respectively.

Profit Calculation

For the calculation of profit, we subtracted the unit cost of production from the product revenue. In PCT units where three products were produced, we averaged the revenue per tonne based on individual product recoveries. Product specific values were supplied by anonymous sources in the industry and consisted of spruce/fir sawlogs at USD $79.97/tonne ($68/ton), spruce/fir pulpwood at $44.10/tonne ($40/ton), hardwood pulpwood at $55.13/tonne ($50/ton), and biomass chips at $38.59/tonne ($35/ton). All product values are mill delivered prices. A second profit calculation included the costs for PCT at $445/ha, the actual cost for PCT in 1986 (Bataineh et al. 2013).

Analysis

Data were analyzed using R (R Core Team 2015) and four additional analysis packages: car (Fox and Weisberg 2011), nlme (Pinheiro et al. 2015), gplots (Warnes et al. 2013) and multcomp (Hothorn et al. 2008)). Two linear mixed-effects models with a random intercept were developed to explain the variation in harvester and feller-buncher productivity. The original blocking of treatment units was included as a random effect while the actual removal, basal area, initial stand conditions, and hardwood content in each treatment unit were included as a fixed effect. The underlying model assumptions for linear regression (normality, equal variances) were all met and data were not transformed.

An analysis of variance in combination with Tukey HSD pairwise group comparison was used to compare the unit cost of production and profit between individual treatments that were thinned by the cut-to-length and whole-tree systems, respectively. Data from the first plot thinned by each machine (plots 10T and 10U) were removed from further analysis as these plots were used as training plots for each operator.

RESULTS

Product Recovery

Product recovery in PCT stands consisted of spruce/fir pulpwood, spruce/fir sawlogs and hardwood pulpwood (Table 3.5). Overall, 54 % of the harvested volume consisted of sawlogs while 39 % and 7 % was spruce/fir pulpwood and hardwood pulpwood, respectively. In non-PCT stands, product recovery was 100 % biomass chips of mixed species.

Table 3.5: Product recovery in PCT stands.

Plot	Block	Prescription (%)*	Spruce/Fir pulp (tonnes)	Spruce/Fir sawlogs (tonnes)	Hardwood pulp (tonnes)	Total (tonnes)
1T	T1	50	18.7	19.9	9.0	47.5
3T	T2	50	17.6	22.7	1.0	41.3
4T	T3	50	23.7	14.9	0.8	39.4
7T	T2	66	17.6	23.4	4.5	45.5
10T	T2	33	17.7	21.9	0.0	39.6
11T	T4	33	13.2	9.1	2.5	24.9
12T	T1	33	7.3	10.0	8.5	25.8
15T	T4	50	19.0	30.8	6.2	56.1
17T	T4	66	11.5	36.4	3.4	51.2
21T	T3	33	15.8	19.2	0.0	35.0
23T	T3	66	14.0	22.0	1.2	37.2
27T	T1	66	16.0	34.6	0.0	50.6

*Removal of standing softwood volume.

Harvester Productivity in PCT Stands

A linear mixed-effects model with a random intercept was developed for the harvester with the covariates of stand density before thinning (DENS), basal area (BA), hardwood component in the stand (HWC), actual removal in tonnes (REM), and piece size of merchantable trees (PIECE) (Equation 3.1, $R^2_{fixed} = 0.36$). The blocking factor (α) was included as a random effect. None of the covariates ($p_{DENS} = 0.456$, $p_{BA} = 0.409$, $p_{HWC} = 0.620$, $p_{REM} = 0.662$, $p_{PIECE} = 0.450$), or any of the interactions, were significant predictors for harvester productivity (PROD). The blocking factor (α) explains 42 % of the random variation in harvester productivity. Average productivity across all three treatments was 7.7 tonnes/PMH (Figure 3.2).

$$PROD = -1.115 + 0.010 \times DENS - 0.635 \times BA - 0.095 \times HWC + 0.045 \times REM + 125.480 \times PIECE + \propto \qquad \text{Equation (3.1)}$$

Feller-Buncher Productivity in Non-PCT Stands

A linear mixed-effects model with a random intercept was developed for the feller-buncher with the covariates of stand density before thinning (DENS), basal area (BA), hardwood component (HWC), and actual removal in tonnes (REM) (Equation 3.2, $R^2_{fixed} = 0.14$). The blocking factor (α) was included as a random effect. None of the covariates ($p_{DENS} = 0.770$, $p_{BA} = 0.915$, $p_{HWC} = 0.877$, $p_{REM} = 0.137$) or any of the interactions were significant predictors for feller-buncher productivity (PROD). The blocking factor (α) explains 90 % of the random variation in feller-buncher productivity observed. Average productivity across all three treatments was 13.0 tonnes/PMH (Figure 3.3).

$$PROD = 4.379 - 0.001 \times DENS - 0.052 \times BA + 0029. \times HWC + 0.172 \times REM + \propto \qquad \text{(Equation 3.2)}$$

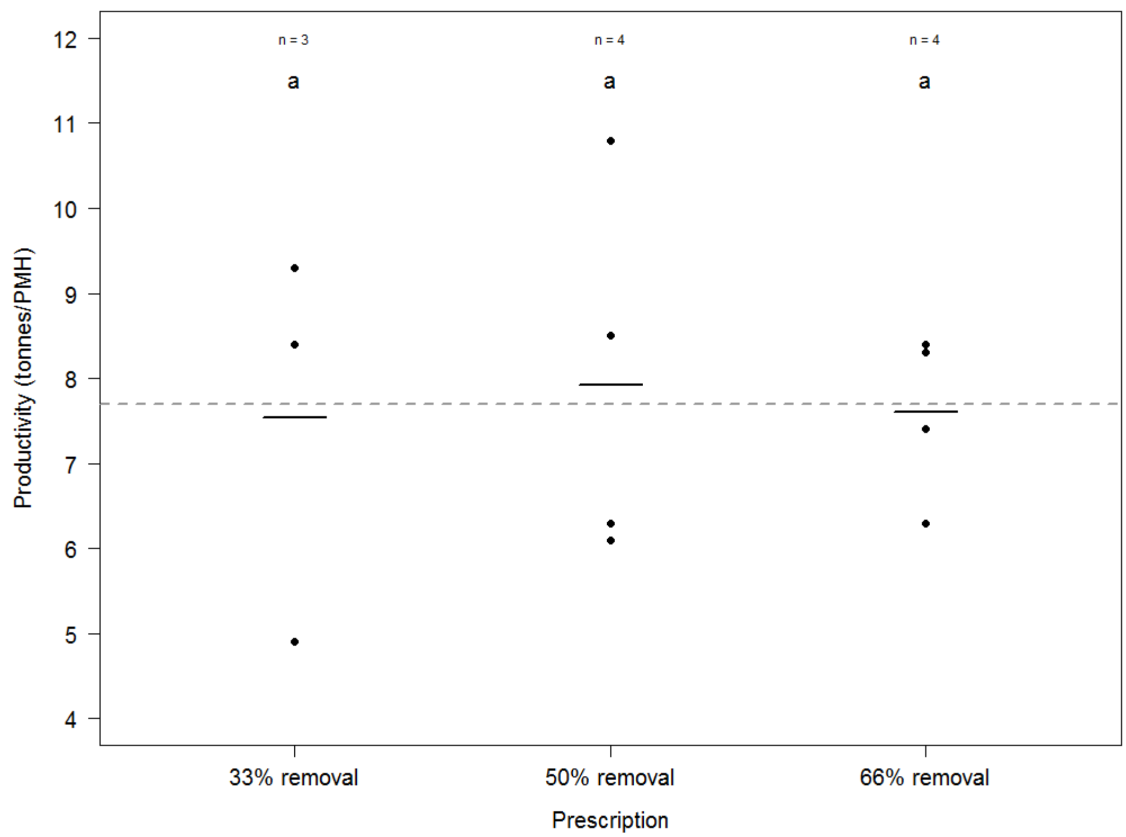

Figure 3.2: Harvester productivity in PCT stands for three different treatments. The dashed line represents overall mean productivity, while the solid black lines represent the average productivity for each prescription. Treatments with the same letter are not significantly different from each other.

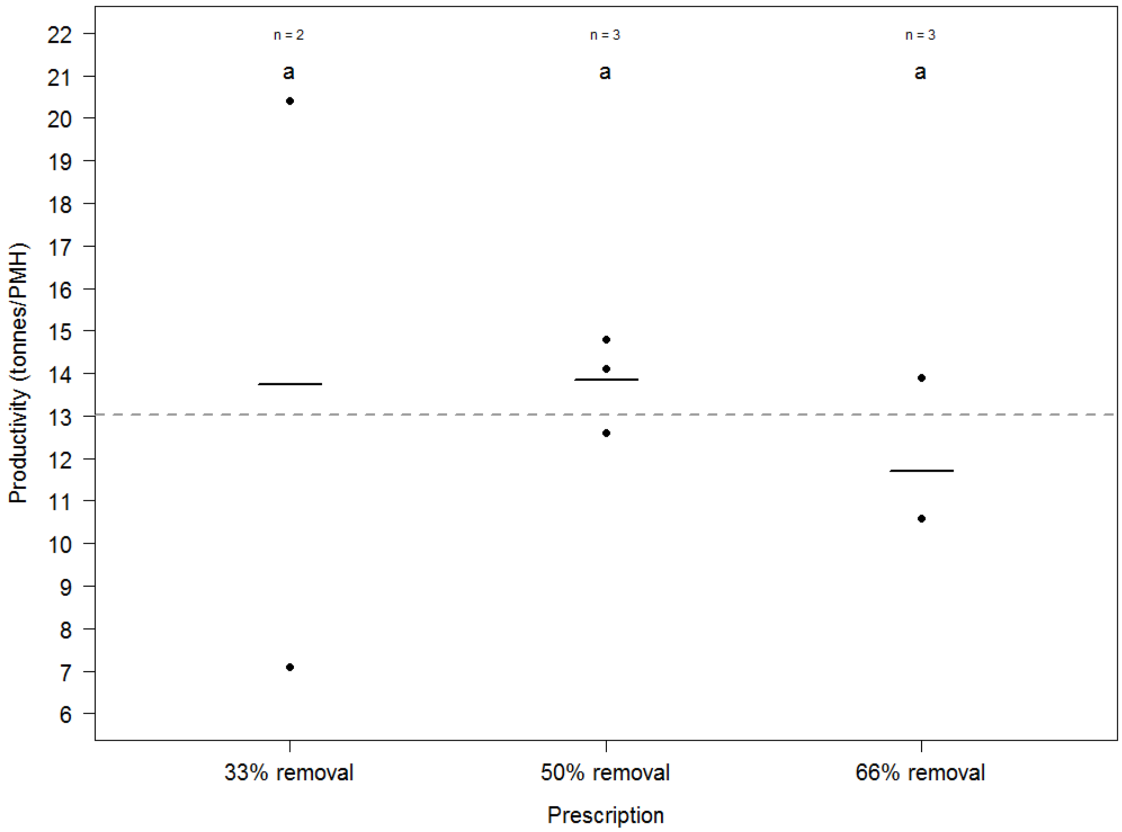

Figure 3.3: Feller-buncher productivity in non-PCT stands for three different treatments. The dashed line represents overall mean productivity, while the solid black lines represent the average productivity for each prescription. Treatments with the same letter are not significantly different from each other.

Unit Cost of Production

The unit cost of production of roundwood from PCT stands ranged from USD \$20.56/tonne to \$50.66/tonne with an average of \$33.46/tonne. Biomass harvest costs from non-PCT stands ranged from \$15.08/tonne to \$34.08/tonne with an average of \$22.33/tonne. An analysis of variance in combination with Tukey HSD pairwise group comparison showed that there is no difference in unit cost of production between individual prescriptions within PCT ($p = 0.309$) and non-PCT ($p = 0.672$) stands, respectively. However, there are differences ($p = 5.86e\text{-}04$) between PCT and non-PCT stands (Figure 3.4). The unit cost of production in PCT and non-PCT treatment units of the same prescription are different from each other with the exception of the 66 % removal prescription. In that prescription there is no difference between the unit cost of production in PCT and non-PCT stands.

Profit

The profits for roundwood from PCT stands ranged from USD \$10.37/tonne to \$42.45/tonne. Profits on wood chips from non-PCT stands ranged from \$4.51/tonne to \$23.51/tonne. An analysis of variance in combination with Tukey HSD pairwise group comparison showed that there is no difference in profit between individual prescriptions within PCT ($p = 0.086$) and non-PCT ($p = 0.672$) stands, respectively (Figure 3.5). Profits between PCT and non-PCT stands are not different from each other with the exception of profits from the 66 % removal prescription ($p = 0.003$). The average profits in PCT and non-PCT stands across all treatments were \$27.59/tonne and \$16.26/tonne, respectively.

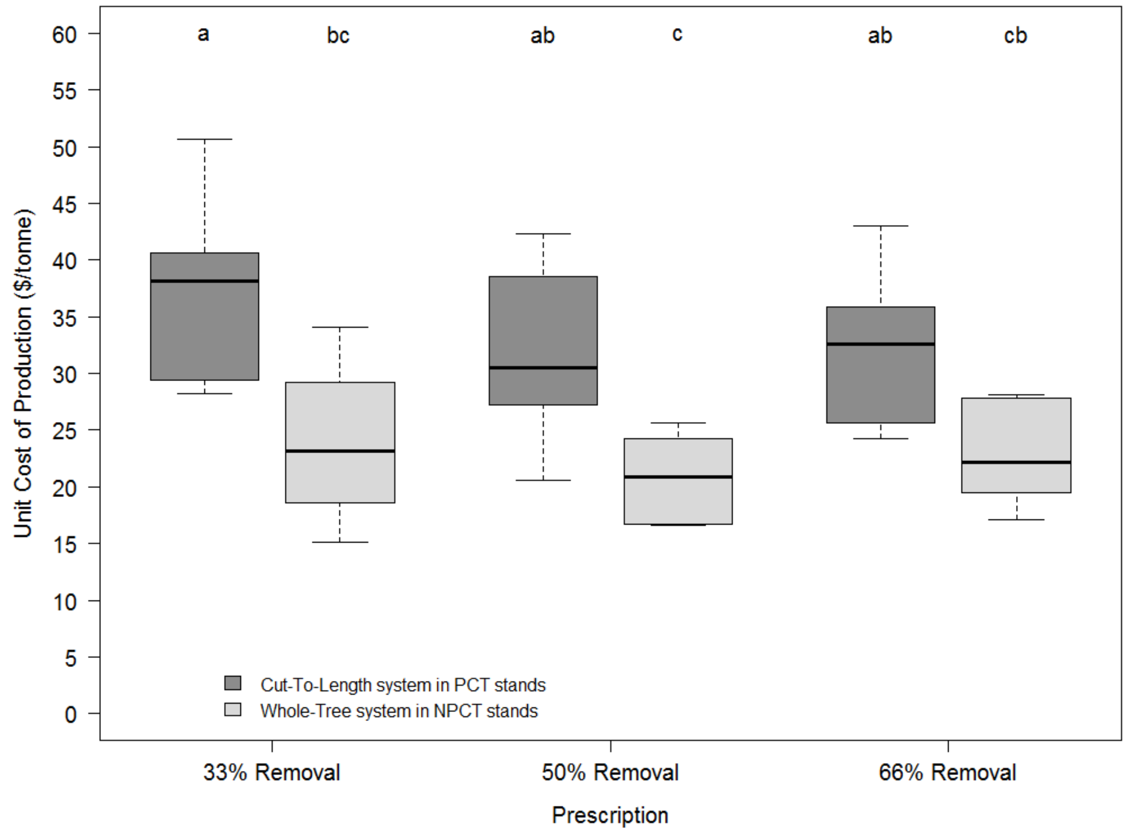

Figure 3.4: Boxplot of unit cost of production ($/tonne) of roundwood and biomass from PCT and non-PCT stands trucked and delivered to a mill. Treatments with the same letter above their box have means that are not significantly different from each other. Bold lines represent the median productivity. The upper and lower whiskers represent the minimum and the maximum, respectively.

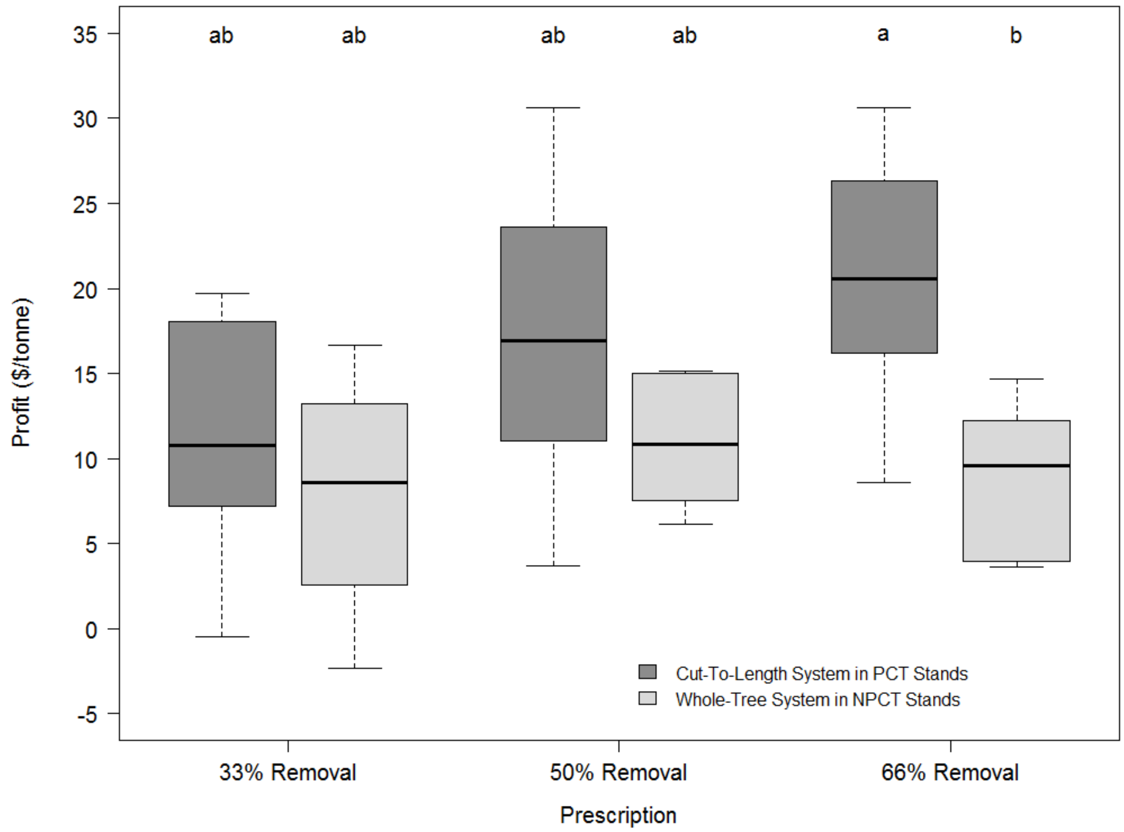

Figure 3.5: Boxplot of profits ($/tonne) of roundwood and biomass from PCT and non-PCT stands trucked and delivered to a mill. Initial costs for PCT treatment have not been discounted for. Treatments with the same letter above their box have means that are not significantly different from each other. Bold lines represent the median productivity. The upper and lower whiskers represent the minimum and the maximum, respectively.

A second profit calculation included the costs for PCT at $445/ha. Without discounting for any interest rate, the results of an analysis of variance show that there is no difference between the profit achieved from harvesting roundwood in PCT stands or biomass chips from non-PCT stands with the same prescription (Figure 3.6). The only difference ($p = 0.024$) exists between the profit gained from harvesting roundwood in PCT stands of a 33 % removal and 66 % removal prescription.

DISCUSSION

Harvester and Feller-Buncher Productivity

Research indicates that several factors influence the productivity of harvesting equipment. Stand density, for example, has been reported to be an influential factor on feller-buncher and harvester productivity (Eliasson 1999; Gingras 1988). In our study we found that neither stand density, basal area, hardwood component, actual removal, or piece size explain the variation in machine productivity. We used a linear-mixed effects model to test for explanatory variables and found that stand density had no explanatory significance even though we operated in stand densities ranging from 1309 to 2594 and 3211 to 5496 trees/ha for harvester and feller-buncher, respectively.

Eliasson (1999) reported that stand density affects harvester productivity the most when harvesting large diameter trees. The reasoning was that directional felling of large trees is more difficult and time-consuming in high density stands. Our harvest site consists of only small-diameter trees with piece sizes of less than 0.17 m^3. We believe that there is no increased difficulty of felling such small trees. One contributing factor to this assertion is that we used a trail spacing of 15.2 m which reduces the distance a machine has to reach into the matrix and therefore allows trees to be pulled or lifted onto the trail more easily.

The amount of volume removed has been shown in other studies to influence harvester and feller-buncher productivity (Li et al. 2006; Légère and Gingras 1998). Three different thinning prescriptions (33 %, 50 %, and 66 % of the standing softwood volume) were implemented in our study. Model results showed that the actual removal intensity did not influence productivity for either harvest system. There may be three reasons for this result: (1) technological advancement of equipment since the 1990s and 2000s when these studies were conducted; (2) use of highly skilled and experienced operators; or, (3) marking of crop trees prior to harvest. The latter might have reduced the time spent making harvesting decisions and hence increased the productivity, especially in the low removal treatment. However, results from an early commercial thinning study in Maine showed that there is no difference in time consumption for common softwood and hardwood species between 10 and 28 cm dbh (Hiesl and Benjamin 2012). Due to the blocking of treatment units, the same range of stand conditions can be found within each prescription. The effect of blocking these treatment units can be seen in the high explanatory power of 42 % and 90 % of the random variation for harvester and feller-buncher productivity, respectively. Taking into consideration all the factors mentioned before, we believe that small tree size is the major reason why there is no difference in productivity between individual prescriptions. Both harvester and feller-buncher productivity compare well with previous results of an early commercial thinning study in a similar stand in Maine (Benjamin et al. 2013) and productivity study results of Hiesl (2013).

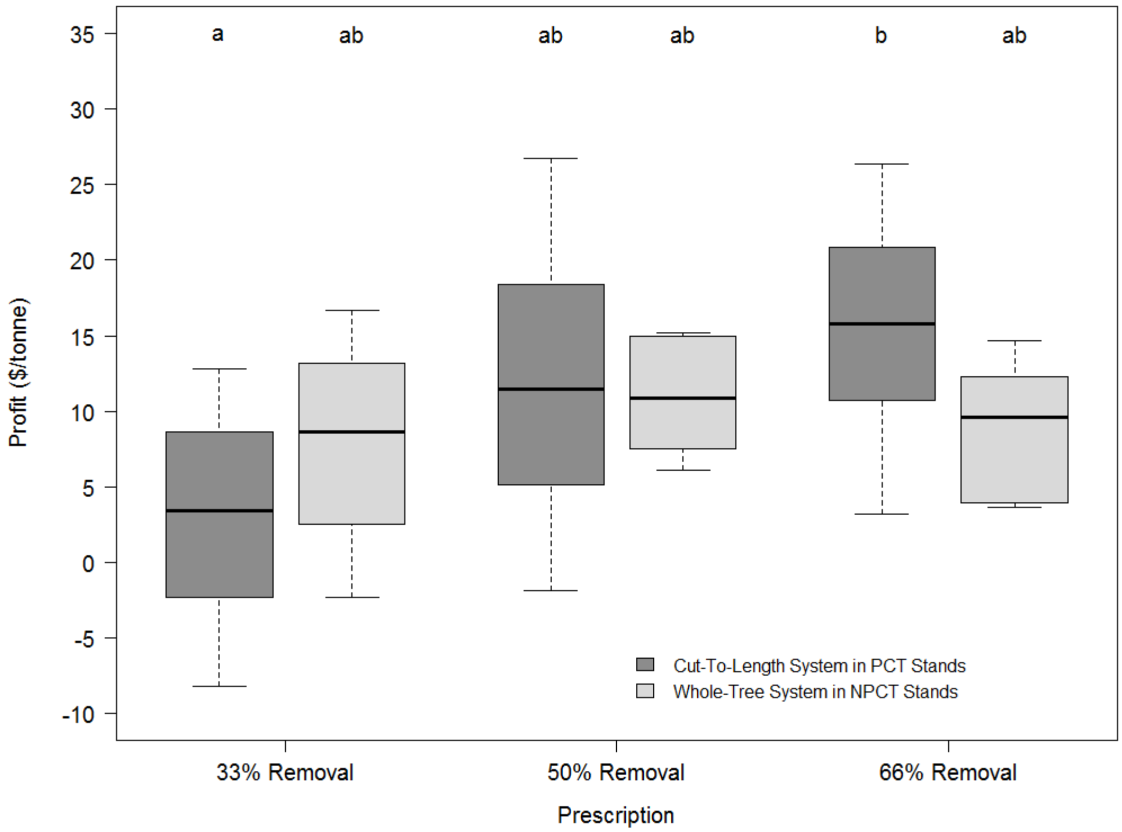

Figure 3.6: Boxplot of profits ($/tonne) of roundwood and biomass from PCT and non-PCT stands trucked and delivered to a mill. Initial costs for PCT treatment have been accounted for, but do not include any interest. Treatments with the same letter above their box have means that are not significantly different from each other. Bold lines represent the median productivity. The upper and lower whiskers represent the minimum and the maximum, respectively.

Commercial thinnings in this region have been observed by the authors to exceed 50 % of the basal area. In our study, this would be reflected in the 33 % and 50 % removal prescriptions. The removal intensities in the 66 % prescription are extreme values that will be used to gain knowledge about tree and stand responses to such measures. Since a higher removal intensity has been linked to a greater number of softwood regeneration (Olson et al. 2014), we are hopeful that this extreme entry will result in an abundance of regeneration. A treatment based on softwood volume removal instead of basal area removal was chosen so that stand and individual tree responses could be compared to results from the Commercial Thinning Research Network (Clune 2013). Equipment operators in the current study had between seven and thirty years of experience working in similar stand conditions. Research indicates that operators can have a large effect on machine productivity (Hiesl 2013; Hiesl and Benjamin 2013a; Purfürst and Erler 2011; Kärhä et al. 2004). The effect of operators on harvester productivity has been as large as 40 % (Kärhä et al. 2004). A recent study in Maine showed that the effect of operator, machine, and stand and site conditions in small-diameter timber stands is up to 7 % for harvesters, 54 % for forwarders and 30 % for grapple skidders (Hiesl 2013). For a feller-buncher, this effect can be as high as 32 % (Hiesl and Benjamin 2013a). As this study was conducted only at one location in Maine with only one operator for each machine, the results are of limited use in other areas and therefore this research should be seen as a case study. Further research is needed to investigate the variation in machine productivity in different locations and with a multitude of operators.

Unit Cost of Production

In this study we made a conscious decision to use two different harvesting systems for PCT and non-PCT stands of the same age to show an option for treatment of high-density, small-diameter stands with a comparison of unit cost of production to PCT stands. This decision was based on unpublished results from an early commercial thinning trial by Benjamin *et al.* (2013) which showed that a harvester in non-PCT stands has an increased number of delays due to thrown chains and breaking trees. Similar results have been seen in unpublished data from a harvest productivity study by Hiesl (2013). Due to increased downtime of a harvester in high-density, small-diameter stands, we can expect that the thinning of such stands with a cut-to-length system is more costly than the thinning of PCT stands and subsequently also more costly than the use of a whole-tree system. We would further expect a loss of harvest volume, as only roundwood would be processed.

The lack of differences between the unit cost of production between individual prescriptions of PCT and non-PCT stands, respectively, is not surprising, as the there was no difference in productivity either. Also not surprising is the lower unit cost of production for biomass chips. This is due to two reasons: (1) the higher productivity of the thinning and extraction equipment; and, (2) the use of whole-trees which increased the total volume harvested. Within each prescription the unit cost of production of roundwood is higher than the one for biomass chips. One exception may be found in the prescription with the highest removal intensity, where the unit cost of production for roundwood and biomass is not different from each other. One reason for this might be the wide range of actual removals of roundwood and biomass. Since common practice in this region is to commercially thin up to 40 % of the basal area, this observed equality of unit cost production in the 66 % removal prescription, however, is not meaningful to the industry, as this represents a basal area removal of between 63 % and 80 %.

Profit

Proper reasoning would imply that producing a higher value product from PCT stands should result in a higher profit. Except for the 66 % removal prescription however, there is no statistical difference between the profits per tonne for any of the other prescriptions. Our explanation for this is twofold: (1) on average, almost twice as much biomass chips than roundwood logs were harvested from the individual treatment units. Such a surplus was enough to balance the revenue from more valuable roundwood logs in the 33 % and 50 % removal prescription; (2) the 66 % removal prescription produced the largest amount of sawlogs across all prescriptions. With sawlogs being the most valuable product, we know that the surplus of biomass chips in that prescription was not enough to balance the revenue.

All these profit calculations, however, were made without including the costs for the initial PCT. When accounting for the costs of PCT without discounting for any interest rate, the results show that the profit is the same for roundwood from PCT stands and biomass chips from non-PCT stands. Once the PCT costs are discounted by any interest rate, the profit of roundwood from PCT stands will decrease even further. These results support the conclusion that high-density stands that have not been treated with PCT can receive a first thinning at the same time that PCT stands would and still generate a profit. However, it has to be acknowledged that one commercial thinning is not the end of forest management in these stands. Rather, it is another step towards creating a softwood stand consisting of sawlog quality trees. Because of that, other treatments will occur in the future and therefore discounting for the initial investment of PCT at the first commercial thinning might not be completely appropriate. The costs for PCT rather need to be discounted for across the total rotation length to investigate whether or not there is a financial gain on doing such a treatment.

Calculations by Bataineh *et al.* (2013) clearly show a higher net present value (NPV) for PCT stands in the Austin Pond study. One major reason for this outcome is that their analysis included sawlogs and pulpwood only. Their calculations did not account for biomass chips, which was the sole product in non-PCT stands in this study. Another reason for their high NPV values is that they used average stumpage values that were much higher than what would have been economically feasible at this site. When looking at the numbers presented in the current study, it becomes clear that the NPV of non-PCT stands is at least as high as the one for PCT stands if not even higher.

CONCLUSION

Several studies show that the use of PCT increases individual tree growth and returns sawlog-sized trees in a shorter period of time (Pitt et al. 2013a; Olson et al. 2012; Weiskittel et al. 2009; Pitt and Lanteigne 2008). Based on stumpage rates and premiums paid for thinned wood, the NPV for PCT stands is higher than for non-PCT stands (Bataineh et al. 2013; Pitt et al. 2013b). However, results from our study show that the unit cost of production in PCT and non-PCT stands are similar. The increased product volume in non-PCT stands makes up for the lower product value of biomass chips and roundwood and leads to similar profits. The outcome of this case study, therefore, is that a first thinning of high-density, small- diameter stands such as the described non-PCT stands using the whole-tree system is economically feasible. One prerequisite, however, is the existence of a biomass market within a 100 km radius. What needs to be investigated in the future is the individual tree response and the regeneration following such thinnings, so that the effectiveness of these treatments can be evaluated.

CHAPTER FOUR:

EVALUATING THE LONG-TERM INFLUENCE OF ALTERNATIVE COMMERCIAL THINNING REGIMES AND HARVESTING SYSTEMS ON PROJECTED NET PRESENT VALUE OF PRECOMMERCIALLY THINNED SPRUCE-FIR STANDS IN NORTHERN MAINE

ABSTRACT

Commercial thinning (CT) is an important silvicultural practice in the northeastern US, but little is known about its long-term influence on stand development and the role of harvest system selection on profitability. To address this question, existing data from a network of plots in Maine were used to project growth forward in time. Specific objectives were to: (1) compare individual CT treatments for their effect on max net present value (NPV), (2) compare individual treatments for their effect on the timing of max NPV, and (3) investigate the effect of three different harvesting systems on max NPV. A regional growth and yield model (Acadian Variant of the Forest Vegetation Simulator) was used to project tree growth and mortality into the future. Harvest costs for three different harvesting systems were estimated based on regional cycle time equations. A stem merchandiser and local product values were used to estimate NPV for all treatments. Results showed that there was no difference in NPV across three timings of thinning, however, there was a difference in NPV between the removal intensities of 33% and 50% relative density reduction. On average, NPV for the 33% removal was 56% higher than for the 50% removal. In addition, the time to reach max NPV after CT was different between, but not within, the two removal intensities. In general, the treatments with a higher removal intensity reach their max NPV earlier (6 to 18 years after CT). Using a

cut-to-length harvesting system resulted in the highest NPV for all three harvesting systems compared. Overall, our results indicate that there is no economic benefit in the final harvest of a stand that has received a PCT treatment, when delaying the first commercial thinning.

INTRODUCTION

Herbicides and precommercial thinning (PCT) have long been used in the early management of conifer forests in North America and Europe (e.g. Hiesl et al. 2015; Bataineh et al. 2013; Olson et al. 2012; Zhang et al. 2009). The use of herbicides has been shown to reduce undesired ground vegetation and increase softwood growth (Harrington et al. 1995; Newton et al. 1992a; Newton et al. 1992b). Herbicide application has especially been an important factor in regenerating spruce (*Picea* spp.) – balsam fir (*Abies balsamea* (L.) Mill.) stands in the Northeastern US and Canada following the harvests due to the spruce budworm (*Choristoneura fumiferana* Clem.) outbreak in the 1970s and 1980s (Newton et al. 1992b). A large number of studies have been conducted to investigate the effects of herbicide treatments on tree growth, species competition, and wildlife biodiversity. Reviews of such studies can be found in Thompson and Pitt (2003), Wagner et al. (2004), and Wagner et al. (2006).

Density management of naturally regenerated spruce-fir stands is needed, especially where herbicide application provided conifers with an early competitive advantage (Newton et al. 1992b). Precommercial thinning (PCT) is a common tool for density management and is widely applied (Nyland 2002; Smith 1986). Usually, PCT is applied to manage density, control composition, accelerate growth, reduce time to merchantability, improve commercial operability, reduce harvesting and processing costs, and increase revenue (Hiesl et al. 2015; Bataineh et al. 2013; Prévost and Gauthier 2012; Olson et al. 2012; Weiskittel et al. 2011; Pitt and Lanteigne 2008; Pelletier and Pitt 2008; Zhang et al. 2006; Varmola and Salminen 2004; Balmer et al. 1978). PCT has been shown to increase diameter and height growth and yield on residual crop trees (Weiskittel et al. 2011; Weiskittel et al. 2009; Pitt and Lanteigne 2008; Zhang et al. 2006). In general, a commercial thinning (CT) is prescribed many years after a PCT treatment to further increase tree growth (Pekol et al. 2012). The benefits of CT on short-term stand stability and growth have been shown by Clune (2013). He analyzed 10-years of growth and yield data from the Commercial Thinning Research Network (Wagner et al. 2001; Wagner and Seymour 2000) in Maine and results suggested that there was a positive influence of early, light thinning on short-term growth and yield. Pelletier and Pitt (2008) showed an increase in growth and yield as a response to CT, and noted a shorter time to grow merchantable trees.

Three of the major long-term studies of herbicide and PCT effects on tree growth in eastern North America are the Green River Study in northwestern New Brunswick, Canada (Pitt and Lanteigne 2008; Baskerville 1959), the Austin Pond Study in westcentral Maine, USA (Newton et al. 1992a; Newton et al. 1992b), and the Commercial Thinning Research Network (CTRN) across the state of Maine (Wagner et al. 2001; Wagner and Seymour 2000). The Green River Study was established between 1959 and 1961 with the goal to study the long-term responses of balsam fir (*Abies balsamea* (L.) Mill.) and red spruce (*Picea rubens* Sarg.) to PCT. Results from this study clearly showed the positive effect of PCT on diameter growth and the subsequent effect of a shorter rotation time (Pitt et al. 2013a). In addition, results from this study showed that the final harvesting productivity in precommercially thinned stands is up to 35% higher than in unthinned stands (Plamondon and Pitt 2013). The Austin Pond Study, with a focus on the response of softwoods and hardwoods to herbicide application, was established in 1977 in a naturally regenerated seven-year old clear-cut. In 1986, half of the study area was treated with PCT, to investigate the response of balsam fir and red spruce (*Picea rubens* Sarg.)(Bataineh et al. 2013). Results of this study showed that herbicides can reduce ground vegetation and hardwood competition significantly enough to allow increased softwood growth (Newton et al. 1992a; Newton et al. 1992b). The combination of herbicide and PCT further allowed for a higher sawlog volume and NPV, compared to unthinned stands (Bataineh et al. 2013). An analysis of harvest costs and NPV at CT in stands with and without PCT treatment showed that there is no difference in NPV between the two treatment conditions (Hiesl et al. 2015; Chapter 3). For the CTRN, six unthinned and six precommercially thinned sites across Maine were chosen to investigate the response of balsam fir and red spruce to CT of differing removal intensities and timings of entry. Saunders et al. (2008) used CTRN data for their analysis and found that the projected quadratic mean diameter of precommercially thinned stands 30 years after treatment is between 3.0 and 5.8 cm larger than in unthinned stands. They further found that the NPV for stands that received PCT and CT treatments are higher and occur earlier than for unthinned stands.

Spruce and fir are the most harvested timber species in Maine (Maine Forest Service 2014) and represent a tremendous economic value. Herbicide application, PCT, and CT are common tools used in the management of spruce-fir stands, however, long-term results of tree growth and financial returns of these treatments are limited in this region (e.g. Hiesl et al. 2015; Bataineh et al. 2013; Pitt et al. 2013c; Saunders et al.

2008). Growth and yield information is available to simulate the growth of existing stands into the future to assess their net present value (NPV) based on timber volume, stumpage rates, and previous treatment costs. Such simulations have been done in the past for other study sites in Maine (Bataineh et al. 2013; Saunders et al. 2008; Daggett 2003). Their limitations, however, are that their projections were provided for a limited number of sites in central Maine, did not include subsequent treatments such as CT, and used a growth and yield model that didn't directly modify predictions to account for PCT and/or CT. With new and specialized harvesting equipment available, there is also a need to assess the influence of harvesting system on optimal rotation time and magnitude of max NPV.

The goal of this study was to understand the long-term response of PCT spruce-fir stands to CT, based on two removal intensities and three different timings of entry. Our specific research objectives were to (1) compare individual CT treatments for their effect on max NPV, (2) compare individual treatments for their effect on the timing of max NPV, and (3) investigate the effect of three different harvesting systems on max NPV. The working hypothesis is that a delayed thinning will return a higher net present value due to an increased timber volume at the time of final harvest.

METHODS

Study Area

For this study, data from six study sites across northern Maine were used. All sites are part of the CTRN and are naturally regenerated, and previously received herbicide and PCT treatments (Wagner et al. 2001). Site composition and structure are influenced by their respective climatic zones. Briggs and Lemin, Jr. (1992) found that Maine is divided into nine climatic zones, and the CTRN study sites represent three of the climatic zones of the north. Parent material of soils is glacial till and alluvium (Ferwerda et al. 1997). All study sites lie within the Acadian forest, a conifer-dominated mixedwood ecosystem that covers much of Maine and the Canadian Maritimes. Red spruce and balsam fir are the most dominant tree species in these stands. Other conifer species include white spruce (*Picea glauca* (Moench) Voss), eastern white pine (*Pinus strobus* L.), black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenburg), eastern hemlock (*Tsuga Canadensis* (L.) Carrière), and northern white-cedar (*Thuja occidentalis* L.). Common hardwood species include red maple (*Acer rubrum* L.), yellow birch (*Betula alleghanensis* Britt.), paper birch (*Betula papyrifera* Marshall), and quaking aspen (*Populus tremuloides* Michx.).

Study Sites

Data from six CTRN sites, each consisting of seven plots, was used for this simulation. Each site consisted of one control plot and six treatment plots including two different removal intensities and three different timings of entry. The CTRN study was established in 2000 and the removal intensities were 33% and 50% relative density reduction with three different timings of entry (2002,2007,2012) that represent the normal timing of thinning, and a five and ten year delay of thinning, respectively (McConville et al. 2003; Wagner and Seymour 2000). All study sites in the CTRN were chosen based on the stands' readiness for a commercial thinning. This means that individual trees were large enough to generate enough revenue to pay for the thinning and provide a profit. Due to the varying degrees of site productivity, the age of these stands ranged from 23 to 42 years. A typical CT would be applied at this age, whereas the two delayed treatments are used to evaluate the effect of such a delay on tree growth and NPV compared to a normal thinning. At some sites, the actual year of harvest varied by one year due to the availability of a logging crew.

Detailed information about the experimental design can be found in Clune (2013) and Wagner et al. (2001). All sites previously received a PCT treatment, were dominated by balsam fir, and consisted of good to excellent site quality (16 – 21 m at 50 years breast-height) (Clune 2013; Wagner et al. 2001). Rectangular permanent plots, 809 m^2 in size, were fully inventoried on an annual or semi-annual basis between 2002 and 2012, and diameter at breast height (DBH) and total tree height were recorded for each tree. Stand density ranged from 384 to 2,046 trees per ha, quadratic mean diameter (QMD) ranged from 15.4 to 23.3 cm, basal area ranged from 12.2 to 46.5 $m^2 \cdot ha^{-1}$, and average tree height ranged from 12.1 to 16.6 m (Table 4.1). For more detailed plot and site information see Table A.1 in the Appendix.

Table 4.1: Stand and site information for six treatments and one control plot in 2012. Values shown are the means across all six study sites with minimum, maximum, and standard deviation in parentheses.

Treatment								
CT Removal (%)	**Delay (yrs)**	**CT Year**	**Age (yrs)**	**Time since PCT (yrs)**	**TPH**	**QMD (cm)**	**BA ($m^2 \cdot ha^{-1}$)**	**Height (m)**
33	0	2002	45 (35; 54;7)	28 (27;29;1)	901 (694;1141;156)	20.9 (19.1;23.0;1.3)	30.4 (27.9;32.6;2.3)	14.7 (12.1;16.6;1.5)
33	5	2007	45 (35; 54;7)	28 (27;29;1)	893 (670;1141;170)	19.5 (18.4;21.8;1.3)	26.4 (17.9;30.2;4.5)	15.0 (14.0;16.5;0.8)
33	10	2012	45 (35; 54;7)	28 (27;29;1)	984 (756;1290;187)	18.3 (17.2;21.5;1.6)	25.4 (21.4;29.9;2.9)	15.0 (12.8;16.6;1.3)
50	0	2002	45 (35; 54;7)	28 (27;29;1)	639 (546;769;83)	22.2 (20.8;23.3;1.0)	24.8 (21.2;32.0;3.8)	14.4 (13.2;16.5;1.3)
50	5	2007	45 (35; 54;7)	28 (27;29;1)	544 (446;670;96)	20.6 (18.6;22.5;1.7)	18.2 (12.2;23.4;3.8)	14.5 (13.1;15.1;0.7)
50	10	2012	45 (35; 54;7)	28 (27;29;1)	591 (384;744;132)	19.2 (16.5;21.7;1.9)	16.6 (14.1;19.7;2.3)	14.8 (12.9;16.4;1.4)
control			45 (35; 54;7)	28 (27;29;1)	1835 (1612;2046;200)	17.3 (15.4;18.7;1.2)	42.9 (37.9;46.5;3.5)	14.6 (13.1;16.5;1.1)

Notes: TPH = trees per hectare; BA = basal area; QMD = quadratic mean diameter

Growth & Yield

Growth and yield for each plot was simulated from the last plot measurement (2012) for 35 years using the Acadian Variant of the Forest Vegetation Simulator (FVS-ACD) (Weiskittel et al. 2012). This variant projects the growth and mortality of individual trees on an annual basis using species-specific equations developed for the Acadian Region. In addition to using FVS-ACD, we also included a newly developed diameter growth modifier for balsam fir and red spruce that adjusts predicted growth of individual trees based on information from the last commercial thinning (Weiskittel et al. 2015). This growth modifier relies on time since commercial thinning, % basal area removed, and the ratio of QMD post- and pre-thinning. We also used individual plot data measured in 2002 and 2007 to calculate net present values for all treatments in the past.

Product Merchandising

For every year in the projection we merchandised individual trees by using an R (R Core Team 2015) based product merchandiser developed by Hutchinson (2014). This merchandiser estimates merchantable sawlog and pulpwood volume based on regional taper and volume equations (Weiskittel and Li 2012; Li et al. 2012). Biomass volume was not estimated or included in this study. Minimum top diameters for all relevant species were 10.2 cm for pulpwood, and between 12.7 and 25.4 cm for sawlogs (depending on species).

Harvest Cost and Revenue

In accordance with values used by Saunders et al. (2008) for a study using the same sites, we assumed a cost of \$500 USD·ha^{-1} (in 2015 dollars) for PCT treatment across all six study sites. The costs for CT were estimated using the approach outlined by Saunders et al. (2008). They used a simplified version of the model of Randolph et al. (2001), who estimated CT harvesting costs using PPHARVST harvest cost simulator (Fight et al. 1999). The thinning system chosen by these authors was a cut-to-length (CTL) system with a machine rate of \$74.56 USD·ha^{-1} for a harvester, and \$51.88 USD·ha^{-1} for a forwarder. As the majority of study sites were thinned using a CTL system (Wagner et al. 2001), this method resulted in a good approximation of the real thinning costs. At the time of thinning, harvest costs and volume removal were not recorded and therefore had to be estimated. Volume removal for each CT was estimated by using average piece size before the thinning and the number of trees removed during the thinning in an equation provided by Saunders et al. (2008). The average piece size was estimated by inserting QMD and stand density before the thinning into an equation provided by Wilson et al. (1999) that was solved for piece size. Saunders et al. also reported a mill delivered product value of \$147.23 USD·m^{-3} that was used for revenue calculation of the CT. This product value is from Maine in the early 2000s and does not reflect current product values for pulpwood, which are between \$40 USD·m^{-3} and \$50 USD·m^{-3}. For comparability of all treatments, however, this value was used in all CT estimations. Detailed information before and after CT for all treatments can be found in Table 4.2.

To estimate final stand harvest costs, lists of trees created by the growth and yield simulation were expanded to represent a one ha harvest block for each plot. The growth and yield simulation returned such a list of trees for every year for 35 years. In this simulation, final stand harvest costs were estimated for every year after the initial tree list, and there was no definition of the final stand in terms of age. Harvest time for three harvesting systems was estimated using regional cycle time equations for harvesting equipment (Hiesl and Benjamin 2015a; Hiesl 2013; Hiesl and Benjamin 2013a; Hiesl and Benjamin 2013c). A cut-to-length (CTL) system consists of a harvester and forwarder, a whole-tree (WT) system consists of a feller-buncher, grapple skidder, and stroke delimber, and a hybrid (HYB) system consists of a feller-buncher, processor, and forwarder. These systems were chosen as they represent harvesting equipment that is commonly used in this region. A processor in a HYB system does not have to fell trees and therefore uses less time to process individual trees. Processor cycle time of the HYB system was estimated using 70% of the estimated harvester cycle time of a CTL system. Research by Simões et al. (2008) suggests that a harvester spends approximately 30% of its time felling trees. Similar results were found by an unpublished video analysis of harvesters from two different studies in Maine. Time consumption for a loader/crane to load one truck was assumed to be 25 min. We used an average skidding and forwarding distance of 300 m, a forwarder payload of 10 m^3, and a bunch size of 3 m^3, which are consistent with regional values.

Harvest costs were calculated using the estimated time consumption for each machine multiplied with the appropriate machine rate (Table 4.3). Machine rates represent averages estimated as part of an early commercial thinning study in Maine (Benjamin et al. 2013). Cost of delivering roundwood to the mill at a round-trip distance of 160 km and a cost of $\$1.67 \cdot km^{-1}$ were also included. This distance was chosen as it represents a common trucking distance in Maine. Payload for one truck was assumed to be 28 m^3, to ensure that the truck and the load are within state specifications of gross weight. Revenue was estimated for every year using the projected merchandised sawlog and pulpwood volume from each plot and multiplying it with average product values of \$72 USD·m^{-3} for sawlogs and \$42 USD·m^{-3} for pulpwood. All product values are based on information from the forest industry in Maine in 2014. We did not adjust product value for possible changes in the future.

Net present value (NPV) is the sum of all cash flows, positive or negative, discounted or compounded to a base year (= 2015). In this study there were three cash flows: PCT costs, CT costs and revenue, and final harvest costs and revenue (Eqn. 4.1). Other management costs of the stand, such as reforestation, and future values past the final harvest are not included.

$$NPV(\$ \cdot ha^{-1}) = \frac{PCT}{(1+i)^{t_1-t}} + \frac{CT_{gross}-HC_{CT}}{(1+i)^{t_2-t}} + \frac{FH_{gross}-HC_{FH}}{(1+i)^{t_3-t}} \qquad \text{Eqn. 4.1}$$

PCT was included as a cost of \$500 USD·ha^{-1}. CT_{gross} and FH_{gross} are gross revenues from the CT and final harvest, respectively, whereas HC_{CT} and HC_{FH} are the harvest costs associated with these treatments. The years of PCT, CT, and final harvest are described by t_1, t_2, and t_3, respectively. The base year, t, is 2015. We used as 4% discount rate, i, based on the adopted recommendation of the US Forest Service in long-term resource planning (Row et al. 1981). NPV was calculated for every year in this simulation.

Table 4.2: Stand and commercial thinning information for six treatments. Values shown are the means across all six study sites with standard deviation in parentheses.

Treatment			Pre-harvest				Post-harvest	
Removal (%)	Delay (yrs)	CT Year	TPH	BA ($m^2 \cdot ha^{-1}$)	QMD (cm)	Piece size (m^3)	BA ($m^2 \cdot ha^{-1}$)	QMD (cm)
33	0	2002	1,691 (252)	31.9 (3.3)	15.6 (1.3)	0.12 (0.03)	19.0 (0.9)	14.0 (1.9)
33	*5*	*2007*	*1,888 (203)*	*36.0 (2.5)*	*15.6 (0.8)*	*0.13 (0.02)*	*21.6 (1.5)*	*14.4 (0.8)*
33	10	2012	1,853 (300)	40.3 (3.0)	16.8 (1.6)	0.16 (0.04)	25.3 (2.9)	15.5 (1.7)
50	0	2002	1,691 (252)	26.6 (2.7)	14.2 (0.7)	0.09 (0.01)	12.5 (1.4)	12.7 (0.84)
50	5	2007	1,692 (313)	30.9 (2.8)	15.4 (1.4)	0.12 (0.03)	14.1 (1.8)	13.8 (1.6)
50	10	2012	1,484 (397)	34.3 (4.6)	17.5 (2.0)	0.17 (0.05)	16.6 (2.2)	16.0 (2.2)

Treatment							
Removal (%)	Delay (yrs)	CT Year	Trees removed	BA removal (%)	Vol. rem. ($m^3 \cdot ha^{-1}$)	Cost ($\$ \cdot ha^{-1}$)	Revenue ($\$ \cdot ha^{-1}$)
33	0	2002	703 (169)	40 (5)	85.4 (27.2)	941 (203)	2,170 (690)
33	*5*	*2007*	*924 (98)*	*40 (4)*	*119.2 (18.8)*	*1,233 (121)*	*3,029 (479)*
33	10	2012	836 (127)	37 (3)	132.6 (16.5)	1,209 (87)	3,370 (419)
50	0	2002	1,084 (171)	53 (3)	99.4 (14.3)	1,294 (173)	2,526 (362)
50	5	2007	1,083 (239)	54 (4)	124.5 (16.9)	1,378 (206)	3,164 (429)
50	10	2012	865 (235)	52 (2)	140.4 (22.0)	1,259 (222)	3,569 (559)

Notes: CT = commercial thinning; TPH = trees per hectare; QMD = quadratic mean diameter; BA = basal area

Table 4.3: Machine rates for all three harvesting systems including labor.

Machine	Machine ($\$\cdot PMH^{-1}$)
Harvester	160
Processor	160
Forwarder	110
Feller-Buncher	140
Grapple Skidder	100
Stroke Delimber	130
Loader/Crane	40

Note: PMH = productive machine hour

Data Analysis

To assess the influence of treatment on the value and timing of max NPV, we developed two linear mixed-effect analysis of variance (ANOVA) models. Since the sites were previously thinned by a CTL system (Wagner et al. 2001), we used a CTL system as our baseline for NPV calculations. For the assessment of the influence of harvesting system and treatment on max NPV, we developed an additional ANOVA model using NPV data from all three harvesting systems simulated in this study. Random effects for plots nested within site were estimated to account for variation from factors that have not been identified and may have influenced the dependent variables. Pairwise comparison tests among thinning treatments were performed using Tukey's method of multiple comparisons at a significance level of 0.05. All analyses were implemented in R (R Core Team 2015) using the nlme (Pinheiro et al. 2015), multcomp (Hothorn et al. 2008), and lsmeans (Lenth and Herve 2015) packages.

RESULTS

Five different variables were measured to evaluate the response of spruce-fir stands to the various CT treatments. All responses were measured from the time of CT and included merchantable volume, gross merchantable volume MAI, percent sawlog volume, and net present value (NPV) differences from the control. With the exception of percent sawlog volume, a light thinning (33% relative density removal) returned higher values than a heavy thinning (50% relative density removal) for all values measured (Figure 4.1). Ten years after thinning all treatments resulted in a percent sawlog volume above 90% of the total merchantable volume.

Total merchantable volume increased over a longer period of time for the light thinning than it did for the heavy thinning. With the heavy thinning, merchantable volume growth slows down approximately 15 years after thinning. Fifteen years after thinning, total merchantable volume ranged from approximately 150 to 400 $m^3 \cdot ha^{-1}$ for both thinning treatments, whereas 35 years after thinning the merchantable volume ranged from approximately 175 to 700 $m^3 \cdot ha^{-1}$. Gross merchantable volume MAI for heavy removal treatments peaked approximately 15 years after thinning. The MAI for light thinnings peaked at a later time, possibly more than 35 years after thinning. With the exception of a light thinning without any delay, all treatments returned a lower NPV than the control plot. The treatment with a light thinning without any delay, however, returned a higher NPV for the first 10 years after thinning (Figure 4.1). See Figure A.1 in the Appendix for NPVs of all treatments and study sites.

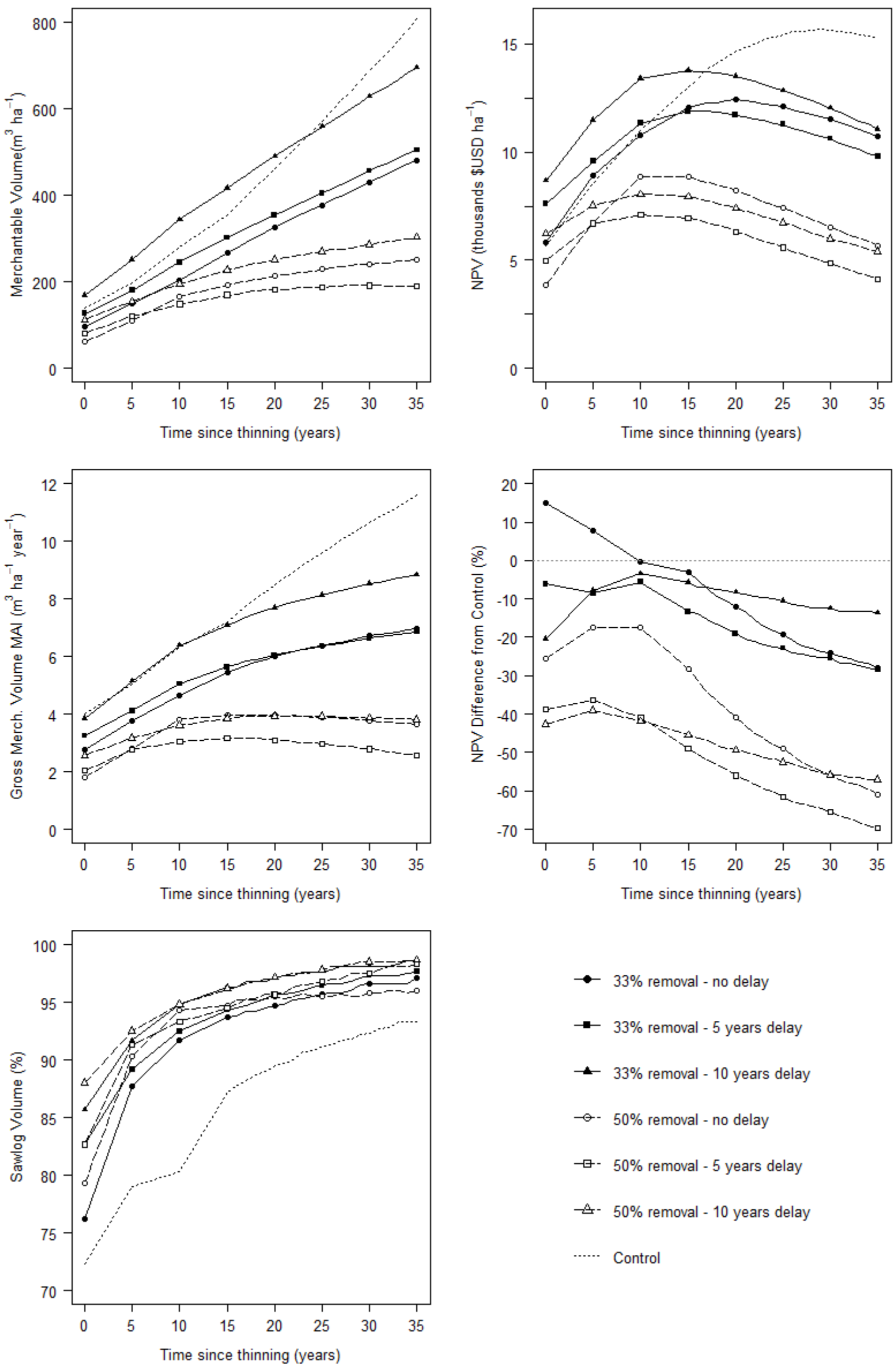

Figure 4.1: Response of treatments to commercial thinning with regards to merchantable volume, gross merchantable volume MAI, percent sawlog volume, net present value, and net present value difference from the control. Time since thinning represents the numbers of years since the last commercial thinning. For the control plot the time since thinning is defined as the time since study establishment in 2002. Data shown represents the average for each treatment across all six study sites.

Treatment Effect on NPV

Across all treatments and final harvest years, the max NPV ranged from \$4,670 USD·ha^{-1} to \$19,484 USD·ha^{-1}. The ANOVA showed that treatment has a significant effect ($p<0.001$) on NPV. Pairwise comparisons indicated that there is no difference between the NPV of the three timings of thinning within the 33% and 50% removal, respectively (Figure 4.2). Results further suggest that the average NPV of the 33% removal (12,848 \$·ha^{-1} (±2,293)) is higher than the average NPV of the 50% removal (8,215 \$·ha^{-1} (±1,779)). The average NPV of the control plot (15,711 \$·ha^{-1} (±4,249)) is the highest across all treatments (Table 4.4). Most of the variation was captured by the fixed effect of treatment, while there was some site to site variation in the relationship of max NPV and treatment (Table 4.5).

Table 4.4: Maximum NPV and rotation length information for all six treatments and control plots at final harvest. All values are based on a CTL harvesting system.

Treatment		Net Present Value				Rotation Length			
Removal (%)	**Delay (yrs)**	**mean**	**min ($)**	**max**	**sd**	**mean**	**min (yrs)**	**max**	**sd**
33	0	12,572	9,353	14,519	1,948	54	47	63	6
33	5	12,997	10,128	16,636	2,415	51	39	65	9
33	10	14,593	11,494	17,938	2,585	56	43	71	9
50	0	9,092	7,769	11,706	1,561	48	36	58	8
50	5	9,173	6,018	11,557	2,360	39	29	48	7
50	10	11,579	7,905	15,084	2,823	44	34	53	7
Control	-	15,711	9,350	19,484	4,249	64	54	72	7

Treatment Effect on Time of max NPV

Across all treatments the timing of max NPV ranged from 6 to 22 years after thinning. The control plot reached max NPV between 25 and 31 years after the CT study began in 2002. The ANOVA showed that treatment has a significant effect ($p<0.001$) on the time of max NPV. Pairwise comparisons indicated that it takes the same time to reach max NPV for plots that either received a 33% or 50% relative density removal (Figure 4.3). However, there are also some similarities between the two removal intensities and timing of thinning. The control plots take the longest time to reach max NPV. Most of the variation was captured by the fixed effect of treatment, while there was some site to site variation in the relationship of timing of max NPV and treatment (Table 4.5). The average rotation length ranges from 39 to 64 years (Table 4.4). A 33% removal intensity resulted in a rotation length of between 41 and 56 years, whereas a 50% removal intensity resulted in a rotation length of between 39 and 48 years. The control plot had the longest rotation time at 64 years. The longer rotation time, however, also resulted in a higher NPV (Figure 4.4). This is also true for the differences in NPV between the 33% and 50% removal intensity.

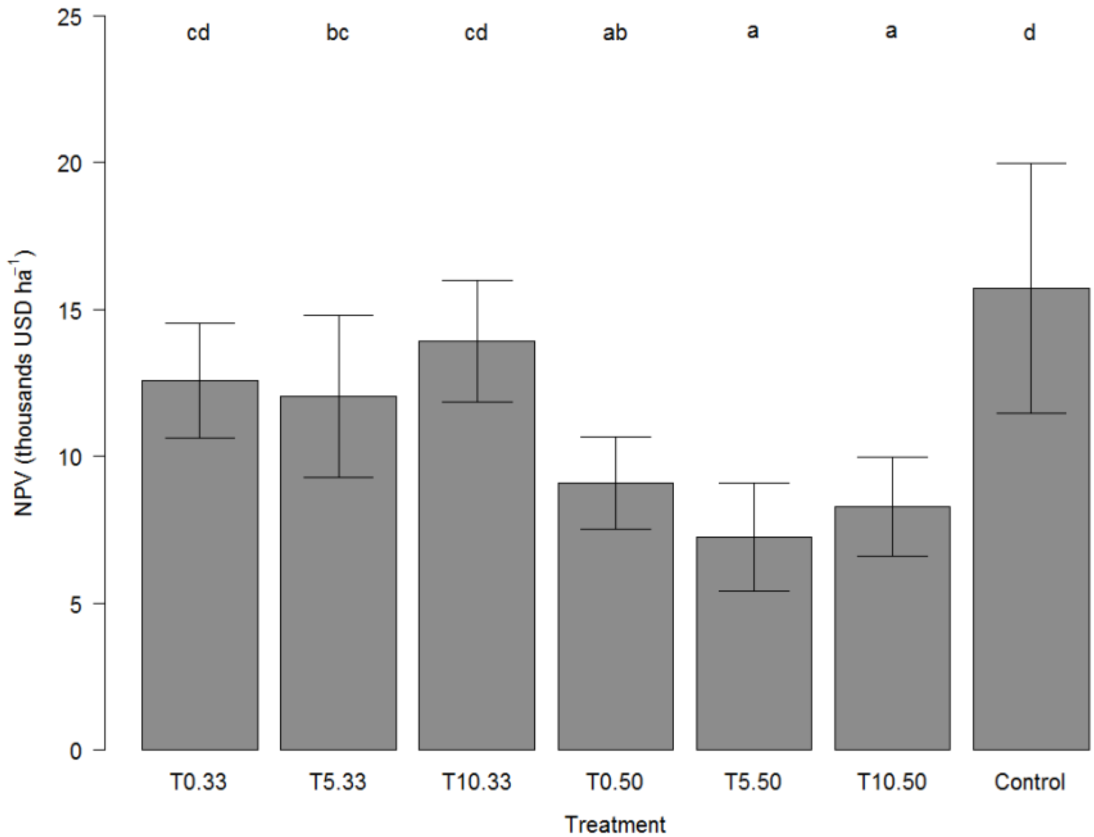

Figure 4.2: Max net present value (NPV) and error bars for six treatments and one control plot across six study sites based on final harvest with a CTL system. The letters above the individual bars show the statistical significance between treatments. The number following the “T” in the treatment labels represents the delay in commercial thinning in years, while the last two numbers represent the relative density removal in percent. Control plots were never commercially thinned.

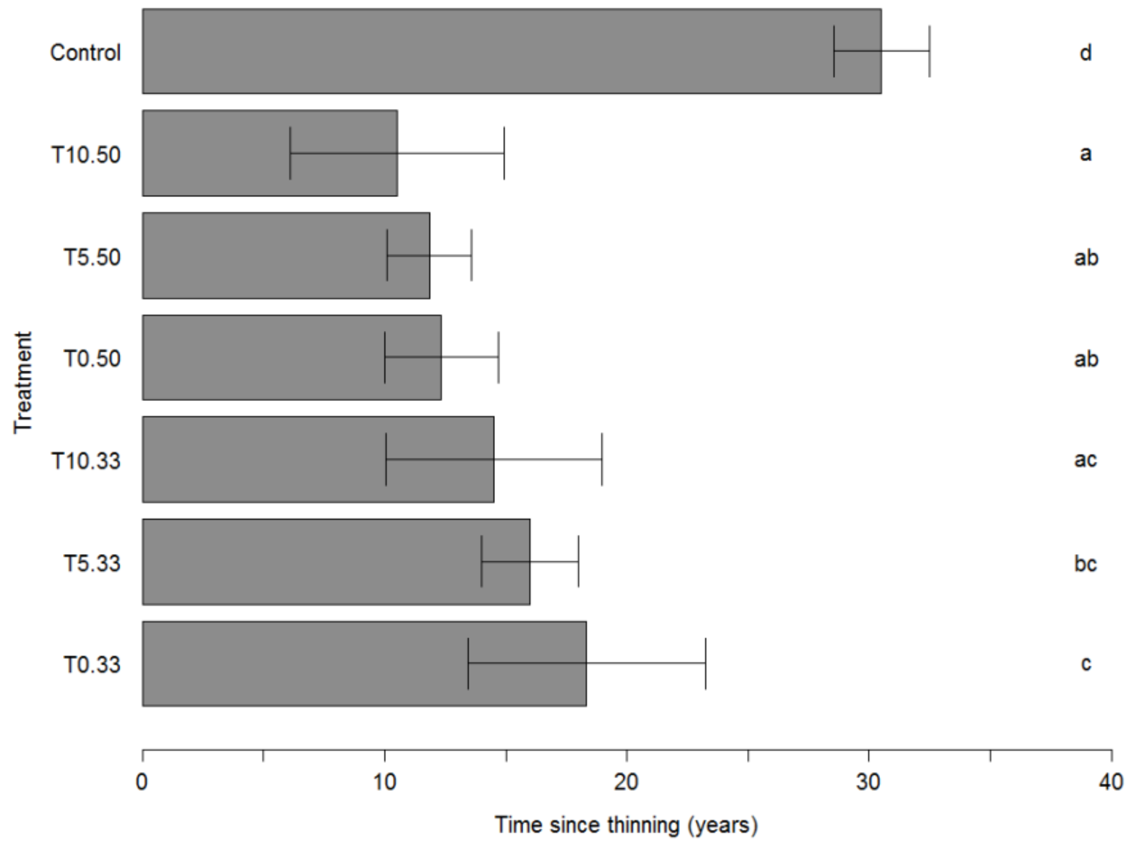

Figure 4.3: Timing of max net present value (NPV) and error bars for six treatments and one control plot across six study sites. The letters to the right of the individual bars show the statistical significance between treatments. The number following the “T” in the treatment labels represents the delay in commercial thinning in years, while the last two numbers represent the relative density removal in percent. Control plots were never commercially thinned, and time since thinning therefore refers to the time since study establishment in 2002.

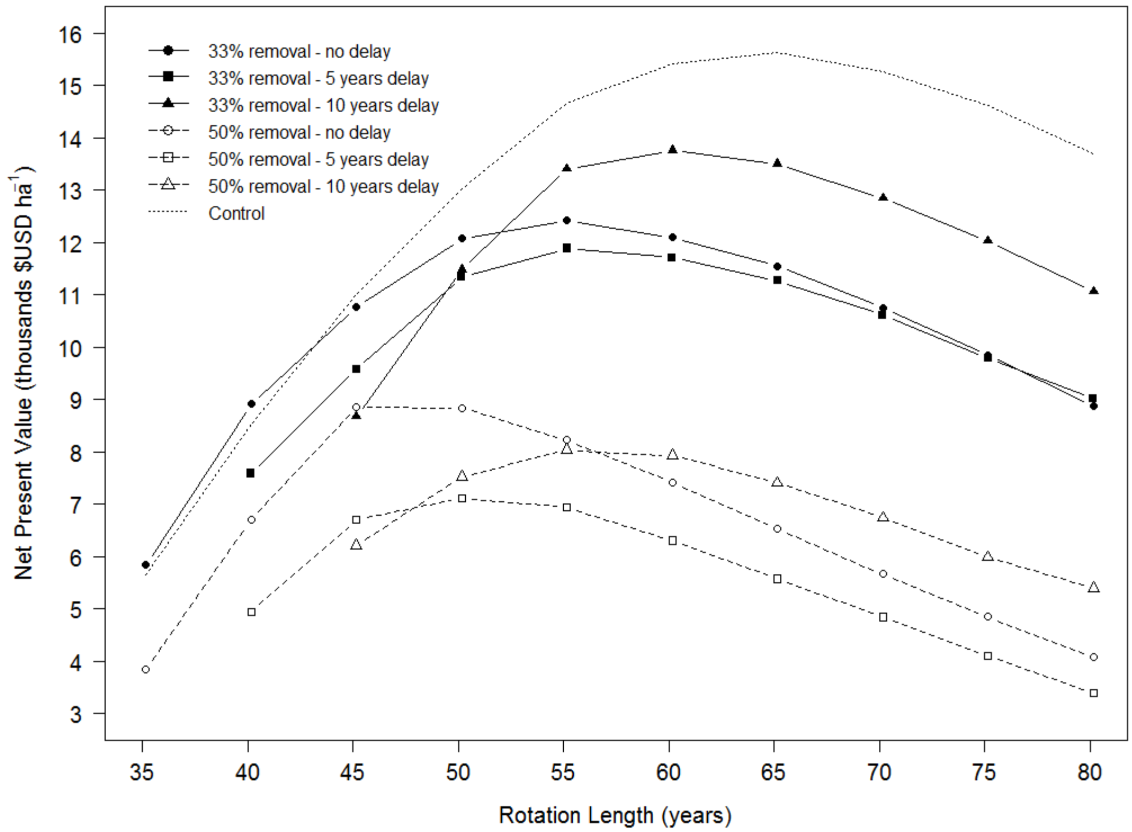

Figure 4.4: Average net present value and rotation length of six treatments and control plots. The beginning of each curve represents the average age at commercial thinning. The curves do not represent any time before the commercial thinning.

Table 4.5: ANOVA results for fixed and random effects on the effect of treatment on max NPV and timing of max NPV. The number following the "T" in the treatment labels represents the delay in commercial thinning in years, while the last two numbers represent the relative density removal in percent.

Max Net Present Value

Fixed effects						***Random Effects***				***R2***	
Treatment	**Value**	**Std. Error**	**DF**	**t-value**	**p-value**	**Variable**	**Std. Dev.**	**Variance**	**Percent**		
Intercept (T0.33)	12,571.98	1004.841	30	12.511	<0.001	STAND	1450.667	2104435	35	R2fixed effects	0.624
T5.33	-526.812	1148.012	30	-0.459	0.650	PLOT (in STAND)	1838.907	3381579	56	R2random effects (STAND)	0.783
T10.33	1,354.43	1148.012	30	1.18	0.247						
T0.50	-3479.961	1148.012	30	-3.031	0.005	Residual	756.446	572210.6	9	R2random effects (all)	0.995
T5.50	-5,313.50	1148.012	30	-4.628	<0.001						
T10.50	-4276.266	1148.012	30	-3.725	<0.001						
Control	3,139.43	1148.012	30	2.735	0.010						

Timing of Max Net Present Value

Fixed effects						***Random Effects***				***R2***	
Treatment	**Value**	**Std. Error**	**DF**	**t-value**	**p-value**	**Variable**	**Std. Dev.**	**Variance**	**Percent**		
Intercept (T0.33)	18.333	1.377	30	13.317	<0.001	STAND	1.959	3.838	34	R2fixed effects	0.772
T5.33	-2.333	1.585	30	-1.472	0.151	PLOT (in STAND)	2.540	6.452	57	R2random effects (STAND)	0.866
T10.33	-3.833	1.585	30	-1.419	0.022						
T0.50	-6.000	1.585	30	-3.786	<0.001	Residual	1.041	1.084	10	R2random effects (all)	0.997
T5.50	-6.500	1.585	30	-4.102	<0.001						
T10.50	-7.833	1.585	30	-4.943	<0.001						
Control	10.167	1.585	30	6.416	<0.001						

Harvesting System Effect on max NPV

Across all treatments, the max NPV ranged from 4,670 $\$\cdot ha^{-1}$ to 19,484 $\$\cdot ha^{-1}$ when using a CTL system, from 4,545 $\$\cdot ha^{-1}$ to 19,184 $\$\cdot ha^{-1}$ when using a HYB system, and from 4,423 $\$\cdot ha^{-1}$ to 18,004 $\$\cdot ha^{-1}$ when using a WT system. The ANOVA showed that both treatment and harvesting system have a significant effect ($p<0.001$) on max NPV. Pairwise comparisons within each individual treatment indicated that using a CTL system results in a higher NPV than using a HYB system or a WT system (Figure 4.5). A final harvest using a CTL system returns a NPV that is between 5.6% and 8.2% higher than that of a WT system. This could mean a gain of \$247 $USD\cdot ha^{-1}$ to \$1,480 $USD\cdot ha^{-1}$ when using CTL system. Most of the variation was captured by the fixed effect of treatment and harvest system, while there was some site to site variation in the relationship of max NPV and treatment and harvest system (Table 4.6).

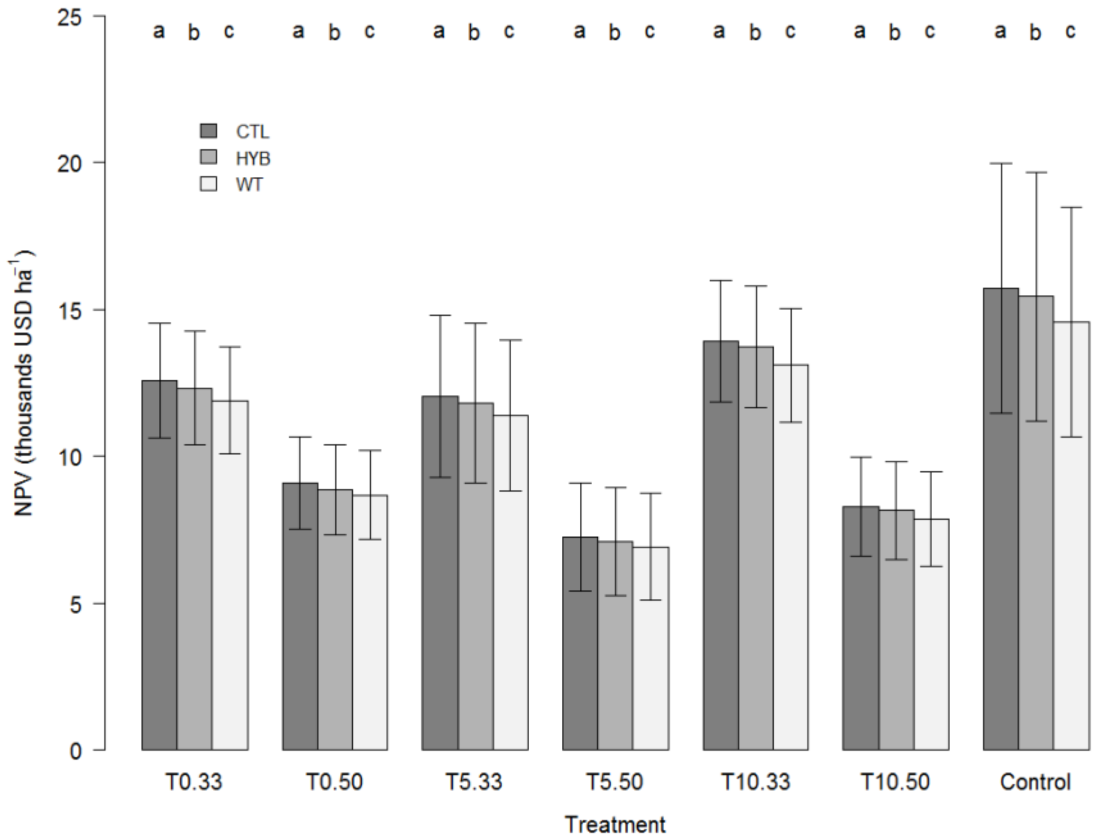

Figure 4.5: Max net present value (NPV) and error bars for six treatments and one control plot across six study sites, with three different harvesting systems. The letters above the individual bars show the statistical significance between systems within each treatment but do not compare across treatments. The number following the "T" in the treatment labels represents the delay in commercial thinning in years, while the last two numbers represent the relative density removal in percent. Control plots were never commercially thinned. Products harvested by a WT system included roundwood only and did not include biomass chips.

Table 4.6: ANOVA results for fixed and random effects on the effect of treatment and harvesting system on max NPV**.**

Fixed effects					
Treatment	**Value**	**Std.**	**DF**	**t-value**	**p-value**
Intercept	12,571.982	981.235	70	12.812	<0.001
T0.50	-3,479.961	1,121.751	30	-3.102	0.004
T5.33	-526.812	1,121.751	30	-0.47	0.642
T5.50	-5,313.502	1,121.751	30	-4.737	<0.001
T10.33	1,354.426	1,121.751	30	1.207	0.237
T10.50	-4,276.266	1,121.751	30	-3.812	<0.001
Control	3,139.434	1,121.751	30	2.799	0.009
HYB	-255.518	59.613	70	-4.286	<0.001
WT	-678.683	59.613	70	-11.385	<0.001
T0.50:HYB	30.715	84.3049	70	0.364	0.717
T5.33:HYB	39.704	84.3049	70	0.471	0.639
T5.50:HYB	104.336	84.3049	70	1.238	0.220
T10.33:HYB	56.566	84.3049	70	0.671	0.504
T10.50:HYB	117.286	84.3049	70	1.391	0.169
Control:HYB	-14.196	84.3049	70	-0.168	0.867
T0.50:WT	268.013	84.3049	70	3.179	0.002
T5.33:WT	22.033	84.3049	70	0.261	0.795
T5.50:WT	350.227	84.3049	70	4.154	<0.001
T10.33:WT	-144.100	84.3049	70	-1.709	0.092
T10.50:WT	246.345	84.3049	70	2.922	0.005
Control:WT	-461.040	84.3049	70	-5.469	<0.001

Random Effects			
Variable	**Std. Dev.**	**Variance**	**Percent**
Site	1414.906	2001959	35
Plot (in Site)	1940.184	3764314	65
Residual	103.252	10661	0

R2	
$R^2_{\text{fixed effects}}$	0.622
$R^2_{\text{random effects (Site)}}$	0.781
$R^2_{\text{random effects (all)}}$	0.9995

Note: CTL = cut-to-length; WT = whole-tree; HYB = hybrid

Sensitivity of NPV

To understand the robustness of our results it was necessary to conduct a sensitivity analysis of the major input variables (skid distance, trucking distance, trucking costs, pulpwood value, sawlog value). Results of such an analysis showed that a change in sawlog value has the greatest impact on NPV (Figure 4.6). For example, a 10% decrease in sawlog value resulted in a 14% decrease in NPV. All other variables impacted NPV by less than 4% for a 20% change in the input variable.

DISCUSSION

Our results showed that delaying a CT does not result in a higher NPV, however, a late CT results in a higher average merchantable volume. NPV is strongly affected by thinning intensity. A light thinning resulted in a higher NPV than a heavy thinning. In this analysis we simulated the use of three different harvesting systems. With a whole-tree harvesting system being the most commonly used system in Maine (Leon and Benjamin 2013) we wanted to investigate whether or not a CTL and hybrid harvesting system would be economically feasible. The results showed that a CTL harvesting system resulted in the highest NPV across all three harvesting systems tested.

A previous study of the same sites and plots with data from 2010 showed that plots with a 33% relative density removal and a five year delayed CT resulted in the highest standing total volume (Clune 2013). At the time of that study, the ten year delayed CT was not yet conducted and therefore was not included in the data analysis. Clune (2013) further noted that the early CT with a 50% relative density reduction resulted in the lowest standing volume among all treatments.

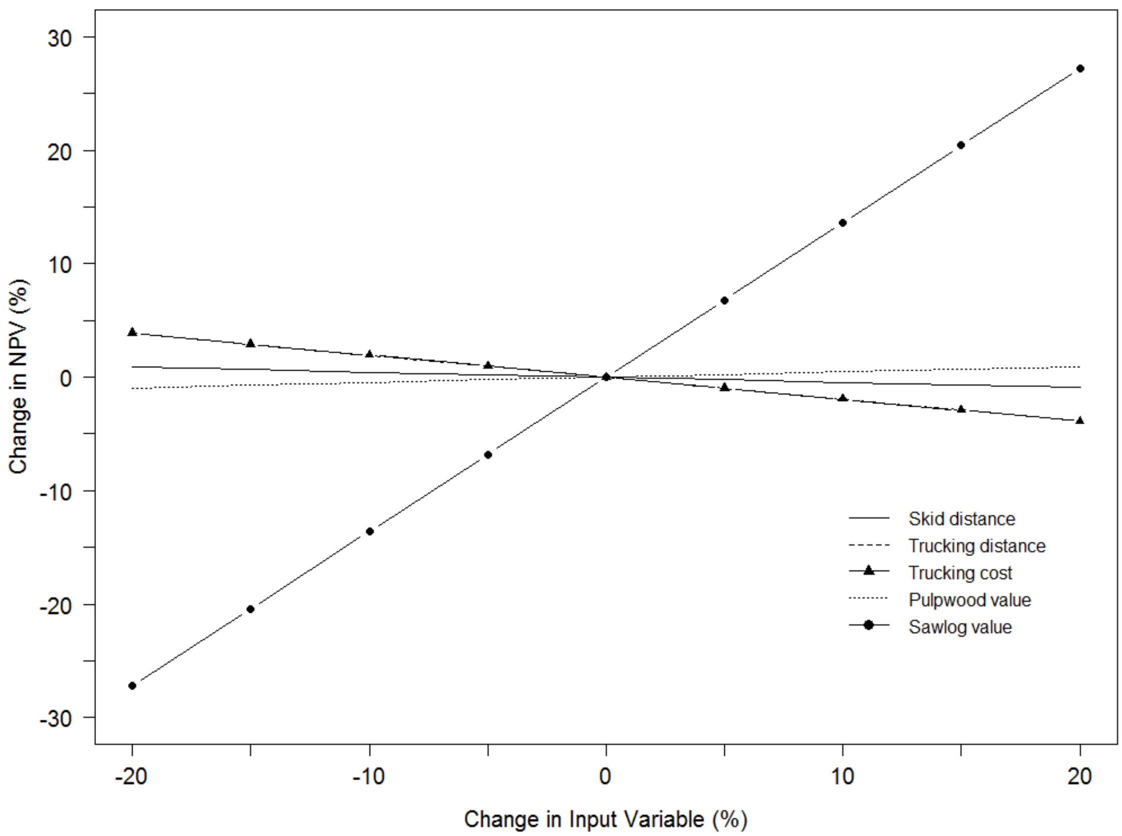

Figure 4.6: Sensitivity of net present value to changes in input variables. A change of 0% in input variables represents the baseline conditions as outlined in this manuscript. The curves for a change in trucking distance and trucking costs overlay each other and are not distinct from each other.

Clune (2013) also reported that the merchantable volume for plots with a 33% reduction in relative density was higher than for plots with a 50% reduction in relative density. It is therefore not surprising that the NPV of plots with a low removal intensity is higher than for plots with a high removal intensity. Clune (2013) also reported that the control plots consisted of the highest merchantable volume, so it is also not surprising that in our study the control plots have the highest NPV across all treatments. This can easily be explained by the fact that control plots were never thinned.

The results clearly show that delaying the first CT by five or ten years has no effect on max NPV for either removal intensity. So it is possible to achieve the same profit whether or not a CT was delayed from the point a stand becomes economically viable for a CT. However, the time when this NPV is achieved is of importance, as this can have implications on the rotation length of a stand. For both removal intensities, the time to reach max NPV after a CT was similar among the three delays in thinning. It is important to consider, however, that this time does not include the additional five or ten years that trees were growing before they were thinned. When including this additional growing time, the ten year delay in thinning resulted in the longest rotation time, for either removal intensity. Research in Norway spruce (*Picea abies* L.) stands in Finland showed that a delayed thinning reduced basal area increment when compared with CT at a normal time or intensive CT (Jaakkola et al. 2006). Their results confirm our findings that a ten year delayed thinning does not return the same NPV in the same amount of time as a CT at normal times or five years delayed. A normal thinning would generally take place as soon as a stand could support a thinning and provide a profit.

A CT is used to decrease stand density and to focus diameter growth on a smaller number of trees (Nyland 2002; Smith 1986). Research in this region confirms that a CT increases the diameter and volume growth of a reduced number of trees in spruce plantations (Pelletier and Pitt 2008). Saunders et al. (2008) reported that the unthinned controls were not able to “catch up” with PCT stands. Such a trend was also seen in the current study, with the QMD of control plots being among the lowest across all study sites. Saunders et al. (2008) also showed that the NPV of control plots is lower and culminates later. In our study, however, the control plots have the highest NPV, but do culminate later than thinned plots.

There are several reasons that might explain this difference. Saunders et al. used a growth and yield model that was not developed for the Acadian forest region, however, they used regional long-term data to calibrate their model. Further, the merchandizing algorithm used by them did not use regional stem and taper equations, and the merchantability dimensions were likely larger than they are today. The merchandizer used in our study used regional stem taper equations (Li et al. 2012) and the latest merchantability dimension. The merchandizer used in our study, however, did not account for a minimum log length and therefore might have overestimated the merchantable pulpwood and sawlog volume.

Another factor that might have led to a difference in NPV is the fact that harvesting costs today are almost twice as high as they were in Saunders et al. (2008) study. In 2000, machine rates for harvester and forwarder were approximately \$75 USD·PMH^{-1} (Productive Machine Hour) and \$52 USD·PMH^{-1}, respectively (Randolph et al. 2001). In 2011, machines rates more than doubled to \$160 USD·PMH^{-1} and \$110·PMH^{-1}, for harvester and forwarder, respectively (Benjamin et al. 2013). In addition to that, product values can vary greatly over time as well. While mill delivered spruce-fir pulpwood was worth approximately \$147 USD·m^{-3} in 2000 (Saunders et al. 2008) this value decreased to between \$40 and \$50 USD·m^{-3} in 2013 (Hiesl et al. 2015).

For our simulation, we assumed that the machine rate and product values stayed constant over a period of 35 years, however, as we have just showed there might be significant changes in these values over time. It is therefore crucial to acknowledge that the numbers at the actual final harvest might be different from the presented results. This difference in harvest costs can easily negate the benefit of CT in terms of NPV. Our sensitivity analysis has shown that a 10% decrease in sawlog value will decrease the NPV by 14%. Other changes of input variables such as trucking distance, skidding distance, trucking costs, and pulpwood value affected NPV by a maximum of 4% when considering a 20% change in these input variables. It is important to note, however, that for all treatment plots a financial return was provided during the CT, whereas the control plots did not yield any financial return until the final harvest. This is important for land managers that require some intermediate financial return on their investment.

The assumptions made in this simulation are important factors that can influence the results. We used average skidding distances and bunch sizes for softwood stands in Maine, based on published and unpublished information from research by Hiesl (2013) and Hiesl et al. (2015). Stand and site conditions, harvesting equipment, and extracting distances are just a few factors that influence machine productivity and vary greatly between states and countries (Hiesl and Benjamin 2013b). This means that the assumptions used for the simulation might not be appropriate in some of the neighboring states. For example, the maximum skidding distance in Maine is approximately 800 m, while a common skidding distance in the state of New York can easily exceed 1,600 m (personal communication with Dr. Steve Bick, principal consultant, Northeast Forests, LLC., Thendara, NY).

Depending on the distance to a mill, average tree diameter, and other factors, the stumpage rate for a given parcel of land can fluctuate immensely. For example, the stumpage rate for spruce/fir pulpwood used by Bataineh et al. (2013) was 11 $\$\cdot ton^{-1}$, which was the average stumpage rate reported by the Maine Forest Service in 2010 (Maine Forest Service 2011). The actual range of stumpage rates in this report, however, was from 2 $\$\cdot ton^{-1}$ up to 22 $\$\cdot ton^{-1}$. These stumpage rates, however, are annually self-reported by loggers, landowners, and foresters, and represent a wide range of stand and site conditions. Therefore, using the average stumpage rate for any parcel might not be representative at all. Instead of using average stumpage values to calculate NPVs (e.g. Bataineh et al. 2013), we estimated harvest costs based on regional cycle time equations (e.g. Hiesl and Benjamin 2013b), using the actual number and size of trees grown in each plot. Results clearly showed that using a CTL harvesting system returns the highest NPV across all treatments. This is a surprising result, as approximately 80% of Maine's timber volume is processed by WT harvesting systems (Leon and Benjamin 2013). With a significant difference of several hundred dollars per ha one would think that more CTL systems would be used to process timber. One of the reasons for the high percentage of timber processed by WT systems might be the initially higher costs for CTL equipment, and the higher complexity to operate such equipment. Harvesters and forwarders can be several hundred thousand dollars more expensive than other machines (Rankin 2015).

Our results also showed that a hybrid system consisting of a feller-buncher, processor, and forwarder returned a lower NPV than a CTL system. This came as a surprise as we expected the hybrid system to be less expensive than a CTL system, mainly due to the high productivity of the feller-buncher and the concentrated processing of trees. One of the major reasons for this result might be the fact that the forwarder cycle time equation used accounted for a larger spacing between logs than what actually would be present on site. Log centration at a harvest site has been shown to influence forwarder productivity (Manner et al. 2013) and therefore the actual forwarder productivity for a hybrid system might be higher. Currently, however, there are no forwarder equations available for this state that would include log spacing as a determining factor.

One of the limitations of this simulation is that we did not include any costs associated with moving harvesting equipment to the harvest site, or any administrative or road building/maintenance costs. Including such numbers is difficult as these costs are highly variable and depend on factors such a distance from a logging contractor and road conditions, but also affect NPV differently with increasing harvest tract size. It is therefore important to highlight that the presented NPVs are very optimistic and will likely be smaller due to additional costs that were not included in this simulation. In addition, we did not include future forest values in our simulation and limited our study to one rotation only. By including future forest values into these calculations the max NPV would typically be reached earlier.

CONCLUSION

With the implications of our assumptions in mind, our conclusions are that there is a margin for the optimal time of thinning of approximately 10 years in which there will be no reduction in max NPV. Clearly, a light thinning will return a higher NPV, but it will also take longer to reach this NPV. For a forest manager with a goal of maximizing his NPV this might be a good choice, however, a forest manager with the goal of returning some revenue in a short period of time, the heavy removal might be a better choice. Such a heavy removal can lead to economically mature stands within 10 to 12 years post CT, whereas a light thinning extends the rotation length for another 4 to 6 years.

Using a CTL harvest system in softwood stands resulted in the highest NPV across all treatments. Even though WT systems are the most commonly used harvesting systems in Maine they returned the lowest NPVs across all sites and treatments. It is therefore important to further increase research in the use of CTL systems in Maine, as these systems might be more profitable than the traditional WT systems. In addition, it is possible that the hybrid system was the most economic system when accounting for the log distribution across a harvest site. It is therefore necessary to conduct further research on the productivity of such harvesting systems in similar stands.

EPILOGUE

The goal of this dissertation is to show various ways that computer simulations can be used in forest operations decision making. Chapters 1 and 2 use a new simulation technique called agent based modeling. The novel aspect here is the modeling of individual agents with their own set of rules and behaviors. For these two chapters I investigated the effect of new technology and the introduction of best processing practices on the idle time, productivity, and unit costs of a system consisting of a stroke delimber and a grapple skidder. I further evaluated the benefits of using one additional grapple skidder. Simulation results clearly showed that due to the dependent nature of the two machines a high percent idle time is unavoidable for at least one of the machines. This idle time increased with longer skidding distances but decreased with increasing bunch size. With the use of this computer simulation I was able to show that an investment in a Geographic Information System (GIS) and a Global Position System (GPS) resulted in a reduced unit cost; however the profit margin was low and the return period high.

The most surprising result from these two chapters was the increase in productivity and decrease in unit cost across the majority of simulated harvests when using one additional grapple skidder. Currently such practices are used on a small scale in Maine; however, with the benefits shown in this simulation it is surprising that such a system is not more widespread. One reason for this might be the high investment cost for a second grapple skidder, and a limited understanding of the benefit of such an investment. Logging contractors are generally occupied running their business by making arrangements for new harvests, staying on top of repair and maintenance, and ensuring that all parties get compensate for their services. Often there are also personal events that occupy a contractors mind. Among all this, it might not even be very high on a contractors list to fully utilize his equipment. With my research there is now an opportunity to transfer knowledge of such a system to the logging industry to highlight the productivity and profitability of such an investment.

In chapter 3 I simulated the thinning costs and profits of three different treatments in the first thinning of research plots that were previously unthinned and precommercially thinned. The use of a computer simulation, based on productivity measures on site, enabled me to compare profits in first thinnings with two different harvesting systems for thinned and unthinned plots, respectively. Results clearly showed that the costs of precommercial thinning can be recovered after the first thinning, however, the profit is no different from the profit of thinning previously unmanaged plots.

Chapter 4 was based on a growth and yield simulation of six study sites with seven treatment plots each. Individual treatments included a 33% and 50% removal of relative stand density and a timing of thinning at optimal time, or 5 or 10 years delayed. The objective was to investigate whether or not there was a treatment effect on net present value (NPV) or optimal time of final harvest based on the timing of thinning or the removal intensity. A secondary focus was to evaluate whether or not there is an economic difference between the uses of three different harvesting systems. Results clearly showed that delaying the first thinning does not impact NPV. However, the removal intensity at the first thinning has a significant impact on NPV. Based on the same harvesting conditions using a cut-to-length harvesting system returns the highest NPV compared to a hybrid system and a whole-tree system.

STRENGTH AND LIMITATIONS

For all simulations of harvest costs and profit I was able to use regional cycle time equations for harvesting equipment (Hiesl and Benjamin 2013c) as well as data collected during a previous study (Hiesl 2013). The use of such a large amount of empirical data lends more credibility to the computer simulations; however, there are also limitations to this study. Chapters 1 and 2 focused on two machines only and are based on one single main trail and one landing. The results shown are further based on a hardwood content of 50%. Many areas in Maine are dominated by softwoods, which might impact the productivity and idle time of the machines.

Further, the data used to verify that the model is an appropriate representation of the real world, was collected at the same harvest sites that were used to develop the cycle time equations that are used in this model. Thus, this was only a model verification and not a model validation as there was no independent data used. A model validation would require independent data with exactly the same conditions as outline in our model. This is difficult, if not even impossible, to achieve, as there are more factors influencing the individual site and stand conditions that are represented in this model. These factors might be known or unknown at this point and can possibly vary greatly within individual stands. I therefore have to outline this lack of model validation as a limitation of this model.

The results of chapter 3 are based on a low number of repetitions and were measured at one site only. Due to the low number of repetitions within this one site it is possible that I did not catch all of the variation in harvesting productivity and cost, and that future studies may show different results. Further, with the use of only one site this study is a case study and might not apply to large areas of forest land in Maine. Chapter

4 investigates the differences in maximum NPV across several treatments at the time of the final harvest. The used growth and yield model might be overestimating the diameter and height of trees, especially in unthinned control plots. This in return, impacts the merchantable volume in these plots. The merchandizer used in this simulation did not account for a minimum length of logs and thus might over predict the merchantable volume as well.

RECOMMENDATIONS

Results from Chapters 1 and 2 indicate that the use of two grapple skidders at harvest sites with small bunch sizes (< 3 tons) lowered the unit cost of production the most. Such conditions can often be found when operating in stands where a light thinning is to be applied. Small bunches, however, can also be encountered when the feller-buncher operator does not pay attention to the bunch size. This leads to the recommendation to inform feller-buncher operators on the effect of small bunch sizes on the overall productivity at a harvest site.

When operating at harvest sites with large bunch sizes (> 3 tons) the results showed that an increased communication using GPS and GIS lowered the unit cost the most. The results, however, also showed that on an average harvest the savings are not big enough to warrant an investment in GPS and GIS for grapple skidders. This is not a big problem, as the same effect can be achieved through an increase in communication between grapple skidder and stroke delimber operators. It is therefore counterproductive to have operators work with each other that do not want to communicate to each other. Reasons for such a behavior could be various and may include personal differences between the operators, a lack of understanding of the benefits of communication, or a lack of motivation to put any effort into the job.

A successful business owner should pay attention to the communication among his or her employees and take appropriate measures to strengthen the collaboration among them. A good way to educate equipment operators is to conduct an operator training workshop with a variety of guest speakers that can highlight the importance of communication or best management practices. Several business owners already conduct such workshops and often included equipment dealers and university researchers to give short presentations on important topics. Mud season is a good time to conduct these workshops, as the time spent during the workshop could not be used to cut wood.

Results from Chapter 3 clearly showed that it is economically feasible to thin high density stands. In our experiment all trees were chipped as the total pulpwood and sawlog volume did not warrant the high costs of a stroke delimber. To avoid chipping pulpwood and sawlog quality trees in these high density stands, it might be appropriate to use a pull-through delimber in combination with a slasher to merchandize logs of higher quality. Pulpwood and sawlogs are more valuable than biomass chips, and the increased revenue might be used to compensate for a longer trucking distance of wood chips. Our results are based on a round-trip trucking distance of 100 miles, however, when operating in the North Maine Woods it is likely to exceed these distances to reach a market. In such cases, the additional revenue from pulpwood and sawlog might still make a harvesting operation profitable. Although results from our experiment of the response of small diameter plots to a commercial thinning are not yet available, the remaining stand should improve in diameter and grow sawlogs in a shorter period of time than control plots would.

Also important to consider in these small diameter stands is to use experienced and proficient operators. In our experiment we used an operator with over 30 years of feller-buncher experience and more than two years of experience operating in small diameter stands. Due to the operators proficiency in such stands we were able to reach high productivities and subsequently finish the thinning with a profit. A comparison of productivities and unit cost with a less experienced operator in a similar stand showed that the productivity was 75% less and that it was not possible to achieve a profit in small diameter stands (Hiesl and Benjamin 2015b). This further highlights the importance of experienced and proficient operations in these challenging stand conditions.

In Chapter 4 results showed that there is no benefit in delaying a commercial thinning by 5 or 10 years in terms of NPV or rotation length. Further, a heavy (50% relative density removal) thinning resulted in a lower NPV than a light (33% relative density removal) thinning. This means that stands should be thinned as early as possible using a light thinning, if the goal is to maximize the NPV in the shortest possible rotation time. If the goal is to shorten the rotation time while accepting some reduced NPV, than an early heavy thinning would be recommended. But even when the most optimal timing of thinning is already past, the results indicated that up to 10 years after this time the NPV will still be the same. To reach this NPV, however, the rotation time will be up to 10 years longer.

At the final harvest, an early light thinning resulted in a less than 5% lower sawlog volume than an early heavy thinning. The same is true for any of the delayed thinning regimes. This information shows that the same proportion of sawlog volume can be achieved regardless of the thinning regime chosen. The only difference is, that with a heavy thinning regime the total merchantable volume at final harvest is lower than with a light thinning. This might affect the overall sawlog supply chain of a company if not accounted for.

Using a cut-to-length (CTL) harvesting system for the final harvest of previously precommercially thinned stands was shown as the most profitable option when operating in softwood stands. Results further showed that using a whole-tree (WT) harvesting system was the least profitable option. Based on annual volume harvested, CTL systems in Maine represent only 13% of such volume (Leon and Benjamin 2013). The numbers of these systems, however, are increasing. For a forest manager operating in softwood stands, it is important to choose the harvest system wisely, as this can have a huge impact on the bottom line. Based on our results, using a CTL system in softwood stands at the final harvest will clearly return the highest possible profit.

FUTURE DIRECTIONS

Agent based modeling is a powerful tool and the research conducted in Chapters 1 and 2 needs to be expanded to include additional pieces of equipment but also to represent the use of more than one main trail. Additional questions that could be answered with a future model could include the selection of the most economical harvesting system based on a given stand condition. The current model as well as the future model should also be used in class room teaching for students, and in workshops and presentation to logging contractors and forest managers. The model represents a valuable tool that can answer important questions of the impact of changes to stand conditions to the overall profitability and productivity of a harvest.

Since Chapter 3 is a case study it is important to expand this research to include more sites with the goal of providing more information about the profitability of PCT to foresters and land managers. Further, this study only compared the commercial thinning costs of previously unthinned and precommercially thinned plots. What is missing, however, is a comparison of predicted harvest costs at the final harvest of these different plots. In addition, the current comparison is based on two different harvesting systems. Future research needs to compare the thinning and final harvest costs of the same harvesting system in both stand conditions to fully evaluate the benefit or PCT.

The study in chapter 4 needs to be expanded to also include stands that were not precommercially thinned. Data from such stands is available through the CTRN and a projection into the future, including harvest costs and profit, should be conducted. The data analysis and simulation modeling have shown that there are problems with over predicting merchantable volume based on the used merchandizer function, but also due to an over prediction of diameter and height growth, especially in control plots. Future simulations need to include an updated growth and yield model, but should also use a product merchandizer that accounts for a minimum log length.

BIBLIOGRAPHY

Abbas, D. et al. 2013. Cost Analysis of Forest Biomass Supply Chain Logistics. *Journal of Forestry* 111(4), pp. 271–281.

Adebayo, A.B. et al. 2007. Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. *Forest Products Journal* 57(6), pp. 59–69.

Allen, T.T. et al. 2008. A structural assessment of the contract logging sector in the Inland Northwest. *Forest Products Journal* 58(5), pp. 27–33.

Andersson, B. and Evans, C.M. 1996. *Harvesting overmature aspen stands in central Alberta*. Special Report SR-112. Pointe Claire, PQ, Canada: Forest Engineering Research Institute of Canada (FERIC)

Arii, K. et al. 2008. A selection harvesting algorithm for use in spatially explicit individual-based forest simulation models. *Ecological Modelling* 211(3-4), pp. 251–266. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0304380007004589 [Accessed: 12 November 2013].

Balmer, W.E. et al. 1978. Financial returns from cultural work in natural loblolly pine stands. *Southern Journal of Applied Forestry* 2(4), pp. 111–117.

Baskerville, G.L. 1959. *Establishment Report - Cleaning and Thinning Young Fir*. Technical Report Project M-443-59. Fredericton, NB, Canada: Department of Northern Affairs and National Resources, Forestry Branch, Maritimes District

Bataineh, M.M. et al. 2013. Long-term response of spruce–fir stands to herbicide and precommercial thinning: observed and projected growth, yield, and financial returns in central Maine, USA. *Canadian Journal of Forest Research* 43(4), pp. 385–395. Available at: http://www.nrcresearchpress.com/doi/abs/10.1139/cjfr-2012-0343 [Accessed: 31 July 2013].

Baumgras, J.E. et al. 1993. Estimating and validating harvesting system production through computer simulation. *Forest Products Journal* 43(11/12), pp. 65–71.

Bazghandi, A. 2012. Techniques , Advantages and Problems of Agent Based Modeling for Traffic Simulation. *International Journal of Computer Science Issues* 9(1), pp. 115–119.

Benjamin, J.G. 2014. *Operational & Economic Aspects of Biomass Harvesting: There is No Free Lunch in the Woods*. Presentation at New England Society of Foresters 2014 Winter Meeting. Nashua, NH, USA: 25 March 2014.

Benjamin, J.G. et al. 2013. Impact of whole-tree and cut-to-length harvesting on postharvest condition and logging costs for early commercial thinning in Maine. *Northern Journal of Applied Forestry* 30(4), pp. 149–155.

Benjamin, J.G. and Hiesl, P. 2013. *What is the Value of Your Time?* Productivity Improvement Workshop for Treeline Inc. Lincoln, ME, USA: May 3, 2013: 3 May 2013.

Bolding, M.C. 2008. Increasing Forestry Machine Utilization. *Sawmill & Woodlot* (February), pp. 23–27.

Borshchev, A. and Filippov, A. 2004. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. In: *The 22nd International Conferences of the System Dynamics Society*. Oxford, England, p. 23.

Bousquet, F. and Le Page, C. 2004. Multi-agent simulations and ecosystem management: a review. *Ecological Modelling* 176(3-4), pp. 313–332. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0304380004000948 [Accessed: 12 November 2013].

Bradley, D.P. et al. 1976. *A Computer Simulation of Full-Tree Field Chipping and Trucking*. Research Paper NC-129. St. Paul, MN, USA: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station

Briggs, R.D. and Lemin, Jr., R.C. 1992. Delineation of climatic regions in Maine. *Canadian Journal of Forest Research* 22(6), pp. 801–811.

Brinker, R.W. et al. 2002. *Machine rates for selected forest harvesting machines*. Circular 296(revised). Auburn, AL: Alabama Agricultural Experiment Station

Brissette, J.C. et al. 1999. Precommercial thinning in a northern conifer stand : 18-year results. *The Forestry Chronicle* 75(6), pp. 967–972.

Brown, D.G. 2006. Agent-based models. In: Geist, H. ed. *The Earth's Changing Land: An Encyclopedia of Land-Use and Land-Cover Change*. Westport, CT, USA: Greenwood Publishing Group, pp. 7–13.

Cavalli, R. et al. 2011. Determination of the forest road network influence on the supply chain for firewood production by discrete event simulation. *Journal of Agricultural Engineering* 4, pp. 41–48.

Clune, P.M. 2013. Growth and development of Maine spruce-fir forests following commercial thinning. Master Thesis. Orono, ME, USA: University of Maine.

Contreras, M.A. and Chung, W. 2011. A Modeling Approach to Estimating Skidding Costs of Individual Trees for Thinning Operations. *Western Journal of Applied Forestry* 26(3), pp. 133–146.

Daggett, R.H. 2003. Long-term effects of herbicide and precommercial thinning treatments on species composition, stand structure, and net present value in spruce-fir stands in Maine: The Austin Pond study. Master Thesis. Orono, ME, USA: University of Maine.

Dixon, G.E. 2002. *Essential FVS: A user's guide to the Forest Vegetation Simulator*. Internal Report (Revised: October 16, 2012). Fort Collins, CO: U.S. Department of Agriculture Forest Service, Forest Management Service Center

Eliasson, L. 1999. Simulation of Thinning with a Single-Grip Harvester. *Forest Science* 45(1), pp. 26–34.

Epstein, J.M. 1999. Agent-Based Computational Models And Generative Social Science. *Complexity* 4(5), pp. 41–60.

Ferwerda, J.A. et al. 1997. *The Soils of Maine*. MAFES Miscellaneous Report 402. Orono, ME, USA: Maine Agricultural and Forest Experiment Station

Fight, R.D. et al. 1999. *Harvesting costs for management planning for ponderosa pine plantations*. General Technical Report PNW-GTR-467. Portland, OR, USA: U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station

Fontalvo-Herazo, M.L. et al. 2011. Simulating harvesting scenarios towards the sustainable use of mangrove forest plantations. *Wetlands Ecology and Management* 19(5), pp. 397–407. Available at: http://link.springer.com/10.1007/s11273-011-9224-4 [Accessed: 12 November 2013].

Fox, J. and Weisberg, S. 2011. *An {R} Companion to Applied Regression*. Second Edi. Thousand Oaks, CA, USA: Sage Publications, Inc.

Garner, G.J. 1978. *Simulation: A decision making aid for managers.* Technical Report TR-30. Pointe Claire, PQ, Canada: Forest Engineering Research Institute of Canada (FERIC)

Gilbert, N. 2007. *AGENT-BASED MODELS*. Thousand Oaks, CA, USA: Sage Publications, Inc.

Gingras, J.-F. 1994. *A Comparative Trial of Two Shortwood Systems in Southwestern Nova Scotia*. Field Note No.: Felling-23. Pointe Claire, PQ, Canada

Gingras, J.-F. 1988. *The effect of site and stand factors on feller-buncher performance*. Technical Report TR-84. Pointe Claire, PQ, Canada: Forest Engineering Research Institute of Canada (FERIC)

Glöde, D. 1999. Single- and double-grip harvesters - productive measurements in final cutting of shelterwood. *International Journal of Forest Engineering* 10(2), pp. 63–74.

Goulet, D. V et al. 1980a. Analysis of Five Forest Harvesting Simulation Models. Part II. Paths, Pitfalls, and Other Considerations. *Forest Products Journal* 30(8), pp. 18–22.

Goulet, D. V et al. 1980b. Five Forest Harvesting Simulation Models. Part I: Modeling Characteristics. *Forest Products Journal* 30(7), pp. 17–20.

Goulet, D. V et al. 1979. Tree-to-Mill Forest Harvesting Simulation Models: Where Are We? *Forest Products Journal* 29(10), pp. 50–55.

Grimm, V. et al. 2010. The ODD protocol: A review and first update. *Ecological Modelling* 221(23), pp. 2760–2768. Available at: http://linkinghub.elsevier.com/retrieve/pii/S030438001000414X [Accessed: 8 November 2013].

Grimm, V. et al. 2006. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* 198(1-2), pp. 115–126.

Han, H.-S. et al. 2004. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. *Forest Products Journal* 54(2), pp. 21–27.

Harrington, T.B. et al. 1995. Interspecific competition and herbicide injury influence 10-year responses of coastal Douglas-fir and associated vegetation to release treatments. *Forest Ecology and Management* 76, pp. 55–67.

Helbing, D. and Balietti, S. 2011. *How to Do Agent-Based Simulations in the Future : From Modeling Social Mechanisms to Emergent Phenomena and Interactive Systems Design*. SFI Working Paper: 2011-06-024. Santa Fe, NM, USA: Santa Fe Institute

Hiesl, P. et al. 2015. Evaluating harvest costs and profit of commercial thinnings in softwood stands in west-central Maine: A Case Study. *The Forestry Chronicle*.

Hiesl, P. 2013. Productivity standards for whole-tree and cut-to-length harvesting systems in Maine. Master Thesis. Orono, ME, USA: University of Maine - School of Forest Resources.

Hiesl, P. and Benjamin, J.G. 2015a. Estimating processing times of harvesters in thinning operations in Maine. *Forest Products Journal*.

Hiesl, P. and Benjamin, J.G. 2015b. Thinning of Small Diameter Stands in Maine. In: *Proceedings of the 38th Council on Forest Engineering: Engineering Solutions for Non-industrial Private Forest Operations*. Lexington, KY, USA: July, 19-22, 2015, p. 10.

Hiesl, P. and Benjamin, J.G. 2013a. A multi-stem feller-buncher cycle-time model for partial harvest of small diameter wood stands. *International Journal of Forest Engineering* 24(2), pp. 101–108.

Hiesl, P. and Benjamin, J.G. 2013b. Applicability of international harvesting equipment productivity studies in Maine, USA: A literature review. *Forests* 4(4), pp. 898–921.

Hiesl, P. and Benjamin, J.G. 2013c. *Harvesting Equipment Cycle Time and Productivity Guide for Logging Operations in Maine*. Miscellaneous Publications 762. Orono, ME, USA: Maine Agricultural and Forest Experiment Station: 2013.

Hiesl, P. and Benjamin, J.G. 2012. *Cycle time analysis of harvesting equipment from an early commercial thinning treatment in Maine*. Proceedings of the 35th Council on Forest Engineering: Engineering New Solutions for Energy Supply and Demand. Roise, J. and Hassan, A. eds. New Bern, NC, USA: Council on Forest Engineering: 12 September 2012.

Holzleitner, F. et al. 2011. Utilization rates and cost factors in timber harvesting based on long-term machine data. *Croatian Journal of Forest Engineering* 32(2), pp. 501–508.

Honer, T.G. 1967. *Standard volume tables and merchantable conversion factors for the commercial tree species of central and eastern Canada*. Information Report FMR-X-5. Ottawa, Ontario: Canadian Department of Forestry and Rural Development. Forest Management Research and Service Institution

Hothorn, T. et al. 2008. Simultaneous Inference in General Parametric Models. *Biometrical Journal* 50(3), pp. 346–363.

Hutchinson, S.F. 2014. Evaluating Variation in Commercial Timber and Land Value for Parcels in the Northeast United States. Master Thesis. Orono, ME, USA: University of Maine.

Huth, A. et al. 2004. Multicriteria evaluation of simulated logging scenarios in a tropical rain forest. *Journal of environmental management* 71(4), pp. 321–33. Available at: http://www.ncbi.nlm.nih.gov/pubmed/15217720 [Accessed: 7 November 2013].

Jaakkola, T. et al. 2006. Wood density of Norway spruce: Responses to timing and intensity of first commercial thinning and fertilisation. *Forest Ecology and Management* 237(1-3), pp. 513–521.

Janssen, M.A. and Ostrom, E. 2006. Governing social-ecological systems. In: Tesfatsion, L. and Judd, K. L. eds. *Handbook of computational economics: Agent-based computational economics*. Vol. 2. Amsterdam: Elsevier, pp. 1465–1509.

Jin, S. and Sader, S. a. 2006. Effects of forest ownership and change on forest harvest rates, types and trends in northern Maine. *Forest Ecology and Management* 228(1-3), pp. 177–186. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378112706001691 [Accessed: 15 December 2014].

Kärhä, K. et al. 2004. Productivity and cutting costs of thinning harvesters. *International Journal of Forest Engineering* 15(2), pp. 43–56.

Kluender, R. et al. 1997. Productivity of Rubber-tired Skidders in Southern Pine Forests. *Forest Products Journal* 47(11/12), pp. 53–58.

Leahy, J.E. et al. 2013. Agent-Based Modeling of Harvest Decisions by Small Scale Forest Landowners in Maine, USA. *International Journal of Forestry Research* 2013, pp. 1–12. Available at: http://www.hindawi.com/journals/ijfr/2013/563068/.

Légère, G. and Gingras, J.-F. 1998. *Evaluation of methods of harvesting with protection of small merchantable stems*. Technical Report-124. Pointe Claire, PQ, Canada: Forest Engineering Research Institute of Canada (FERIC)

Lenth, R. V and Herve, M. 2015. *lsmeans: Lest-Squares Means. R package version 2.16*.

Leon, B. and Benjamin, J.G. 2013. *A Survey of Business Attributes, Harvest Capacity and Equipment Infrastructure of Logging Businesses in the Northern Forest*. The Northern Forest Logging Industry Assessment. Orono, ME, USA: University of Maine

Li, R. et al. 2012. Regional stem taper equations for eleven conifer species in the Acadian Region of North America: Development and Assessment. *Northern Journal of Applied Forestry* 29(1), pp. 5–14.

Li, Y. et al. 2006. Production economics of harvesting small diameter hardwood stands in central Appalachia. *Forest Products Journal* 56(3), pp. 81–86.

Maine Forest Service 2014. *2012 Wood Processor Report*. Annual Report [Updated March 12, 2014]. Augusta, ME, USA: Department of Agriculture, Conservation and Forestry - Maine Forest Service - Forest Policy and Management Division

Maine Forest Service 2011. *2010 Stumpage Prices*. Annual Report. Augusta, ME, USA: Department of Conservation, Maine Forest Service, Forest Policy and Management Division

Manner, J. et al. 2013. Effects of the number of assortments and log concentration on time consumption for forwarding. *Silva Fennica* 47(4), pp. 1–19.

Manson, S.M. 2003. Validation and Verification of Multi-Agent Systems. In: Janssen, M. A. ed. *Complexity and Ecosystem Management: The Theory and Practice of Multi-Agent Approaches*. Northhampton, MA,USA: Edward Elgar Publishers, pp. 63–74.

McCaskill, G.L. et al. 2011. *Maine's Forests 2008*. Resource Bulletin NRS-48. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station

McConville, D.J. et al. 2003. Study Site Establishment and Measurement of the Commercial Thinning Research Network. In: *Cooperative Forestry Research Unit 2003 Annual Report*. Orono, ME, USA: University of Maine, pp. 24–25.

NESFA 2007. *The Economic Importance and Wood Flows from Maine ' s Forests , 2007*. North East State Foresters Association

Newnham, R.M. 1968. Simulation Models in Forest Management and Harvesting. *The Forestry Chronicle* 44(1), pp. 7–13.

Newton, M. et al. 1992a. Young Spruce-Fir Forests Released by Herbicides I . Response of Hardwoods and Shrubs. *Northern Journal of Applied Forestry* 9, pp. 126–130.

Newton, M. et al. 1992b. Young Spruce-Fir Forests Released by Herbicides II . Conifer Response to Residual Hardwoods and Overstocking. *Northern Journal of Applied Forestry* 9, pp. 130–135.

Nyland, R.D. 2002. *Silviculture: Concepts and Applications*. 2nd ed. New York, NY, USA: McGraw-Hill.

Olson, M.G. et al. 2014. Commercial thinning stimulates natural regeneration in spruce – fir stands. *Canadian Journal of Forest Research* 44, pp. 173–181.

Olson, M.G. et al. 2012. Forty years of spruce–fir stand development following herbicide application and precommercial thinning in central Maine, USA. *Canadian Journal of Forest Research* 42(1), pp. 1–11. Available at: http://www.nrcresearchpress.com/doi/abs/10.1139/x11-132 [Accessed: 31 July 2013].

Pekol, J. et al. 2012. Influence of Commercial Thinning on Stand & Tree-Level Mortality Patterns of Balsam Fir and Red Spruce Forests in Maine with & without Precommercial Thinning. In: Roth, B. E. ed. *Cooperative Forestry Research Unit: 2011 Annual Report*. Orono, ME: University of Maine.

Pelletier, G. and Pitt, D.G. 2008. Silvicultural responses of two spruce plantations to midrotation commercial thinning in New Brunswick. *Canadian Journal of Forest Research* 38(4), pp. 851–867. Available at: http://www.nrcresearchpress.com/doi/abs/10.1139/X07-173 [Accessed: 9 September 2013].

Pinheiro, J. et al. 2015. *nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-120*.

Pitt, D.G. et al. 2013a. Effects of precommercial thinning on the forest value chain in northwestern New Brunswick : Part 1 – Roundwood production and stumpage value. *The Forestry Chronicle* 89(4), pp. 446–457.

Pitt, D.G. et al. 2013b. Effects of precommercial thinning on the forest value chain in northwestern New Brunswick : Part 6 – Estimating the economic benefits. *The Forestry Chronicle* 89(4), pp. 502–511.

Pitt, D.G. and Lanteigne, L. 2008. Long-term outcome of precommercial thinning in northwestern New Brunswick: growth and yield of balsam fir and red spruce. *Canadian Journal of Forest Research* 38(3), pp. 592–610. Available at: http://www.nrcresearchpress.com/doi/abs/10.1139/X07-132 [Accessed: 13 August 2013].

Plamondon, J. and Pitt, D.G. 2013. Effects of precommercial thinning on the forest value chain in northwestern New Brunswick : Part 2 – Efficiency gains in cut-to-length harvesting. *The Forestry Chronicle* 89(4), pp. 458–463.

Polley, H. 1987. Anwendung eines digitalen stochastischen Modells zur Kalkulation technologisch bedingter Wartezeiten. *Beiträge für die Forstwirtschaft* 21(2), pp. 72–77.

Prévost, M. and Gauthier, M.M. 2012. Precommercial thinning increases growth of overstory aspen and understory balsam fir in a boreal mixedwood stand. *Forest Ecology and Management* 278, pp. 17–26.

Purfürst, F.T. 2010. Learning Curves of Harvester Operators. *Croatian Journal of Forest Engineering* 31(2), pp. 89–97.

Purfürst, F.T. and Erler, J. 2011. The human influence on productivity in harvester operations. *International Journal of Forest Engineering* 22(2), pp. 15–22.

R Core Team 2015. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing

Railsback, S.F. and Grimm, V. 2012. Sensitivity, Uncertainty, and Robustness Analysis. In: *Agent-Based and Individual-Based Modeling. A Practical Introduction*. Princeton, NJ, USA: Princeton University Press, pp. 291–308.

Ranatunga, K. et al. 2008. Effects of harvest management practices on forest biomass and soil carbon in eucalypt forests in New South Wales, Australia: Simulations with the forest succession model LINKAGES. *Forest Ecology and Management* 255(7), pp. 2407–2415. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378112708000303 [Accessed: 12 November 2013].

Randolph, K.C. et al. 2001. *ThinME: User's Guide*. Cooperative Forestry Research Unit Report 357. Orono, ME, USA: University of Maine

Rankin, J. 2015. Mechanical harvesting - The future is here [Online]. Available at: http://www.forestsformainesfuture.org/fresh-from-the-woods-journal/mechanical-harvesting-the-future-is-here.html [Accessed: 1 January 2015].

Row, C. et al. 1981. Discount Rate for Long-Term Forest Service Investments. *Journal of Forestry* 79(6), pp. 367–376.

Saunders, M.R. et al. 2008. *Thinning Regimes for Spruce-Fir Stands in the Northeastern United States and Eastern Canada*. Orono, ME, USA: Cooperative Forestry Research Unit

Seidl, R. et al. 2012. An individual-based process model to simulate landscape-scale forest ecosystem dynamics. *Ecological Modelling* 231, pp. 87–100. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0304380012000919 [Accessed: 12 November 2013].

Seymour, R.S. 1995. The northeast region. In: Barrett, J. W. ed. *Regional Silviculture of the United States*. 3rd ed. New York, NY, USA: Wiley, pp. 31–79.

Shifley, S.R. et al. 2006. Simulated effects of forest management alternatives on landscape structure and habitat suitability in the Midwestern United States. *Forest Ecology and Management* 229(1-3), pp. 361–377. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378112706002659 [Accessed: 12 November 2013].

Simões, D. et al. 2008. *Technical and economical evaluation of harvester cut-to-length system in first cut eucalyptus forest*. Proceedings of CIGR International Conference of Agricultural Engineering. XXXVII Congresso Brasileiro De Engenharia Agricola – CONBEA. Iguassu Falls City, Brazil: 31 August 2008.

Smith, D.M. 1986. *The Practice of Silviculture*. 8th ed. New York, NY: John Wiley & Sons, Inc.

Spinelli, R. et al. 2010. Productivity standards for harvesters and processors in Italy. *Forest Products Journal* 60(3), pp. 226–235.

Stone, I.J. et al. 2011. Applying Innovation Theory to Maine's Logging Industry. *Journal of Forestry* 109(8), pp. 462–469.

Thompson, D.G. and Pitt, D.G. 2003. A review of Canadian forest vegetation management research and practice. *Annals of Forest Science* 60(7), pp. 559–572. Available at: http://www.edpsciences.org/10.1051/forest:2003060 [Accessed: 21 August 2013].

Tian, S. 2002. Effect of Precommercial Thinning on Root Develpment and Root and Butt Decay Incidence of Red Spruce and Balsam Fir. Orono, ME, USA: University of Maine.

Timber Harvesting 2011. 2011 Logging Business Survey: Big Squeeze [Online]. Available at: http://www.timberharvesting.com/2011-logging-business-survey-big-squeeze/ [Accessed: 7 August 2015].

Varmola, M. and Salminen, H. 2004. Timing and intensity of precommercial thinning in Pinus sylvestris stands. *Scandinavian Journal of Forest Research* 19(2), pp. 142–151.

Wagner, R.G. et al. 2006. The role of vegetation management for enhancing productivity of the world's forests. *Forestry* 79(1), pp. 57–79. Available at: http://forestry.oxfordjournals.org/cgi/doi/10.1093/forestry/cpi057 [Accessed: 9 September 2013].

Wagner, R.G. et al. 2004. The role of herbicides for enhancing forest productivity and conserving land for biodiversity in North America. *Wildlife Society Bulletin* 32(4), pp. 1028–1041.

Wagner, R.G. et al. 2001. Commercial Thinning Research Network. In: *Cooperative Forestry Research Unit 2001 Annual Report*. Orono, ME, USA: University of Maine, pp. 23–35.

Wagner, R.G. and Seymour, R.S. 2000. Commercial Thinning Research Network. In: *Cooperative Forestry Research Unit 2000 Annual Report*. Orono, ME, USA: University of Maine, pp. 21–27.

Wang, J. et al. 2004. Production and cost analysis of a feller-buncher and grapple skidder in central Appalachian hardwood forests. *Forest Products Journal* 54(12), pp. 159–167.

Wang, J. and LeDoux, C.B. 2003. Estimating and Validating Ground-Based Timber Harvesting Production Through Computer Simulation. *Forest Science* 49(1), pp. 64–76.

Warnes, G.R. et al. 2013. gplots: Various R programming tools for plotting data. R package version 2.11.3 [Online]. Available at: http://cran.r-project.org/package=gplots.

Weiskittel, A. and Li, R. 2012. *Development of regional taper and volume equations: Hardwood species*. Cooperative Forestry Research Unit 2011 Annual Report. Roth, B. E. ed. Orono, ME, USA: University of Maine

Weiskittel, A.R. et al. 2015. Extending the Acadian variant of FVS to managed stands (in press). In: *Cooperative Forestry Research Unit 2014 Annual Report*. Orono, ME, USA: University of Maine.

Weiskittel, A.R. et al. 2012. Refinement of the Forest Vegetation Simulator Northeast variant growth and yield model: Phase III. In: Roth, B. E. ed. *Cooperative Forestry Research Unit 2011 Annual Report*. Orono, ME, USA: University of Maine, pp. 85–93.

Weiskittel, A.R. et al. 2011. Stand structure and composition 32 years after precommercial thinning treatments in a mixed northern conifer stand in central Maine. *Northern Journal of Applied Forestry* 28(2), pp. 92–96.

Weiskittel, A.R. et al. 2009. Long-Term Effects of Precommercial Thinning on the Stem Dimensions, Form and Branch Characteristics of Red Spruce and Balsam Fir Crop Trees in Maine, USA. *Silva Fennica* 43(3), pp. 397–409.

Wilensky, U. 1999. *NetLogo*. Evanston, IL, USA: Center for Connected Learning and Computer-Based Modeling, Northwestern University

Wilson, D.S. et al. 1999. Density Management Diagram for Northeastern Red Spruce and Balsam Fir Forests. *Northern Journal of Applied Forestry* 16(1), pp. 48–56.

Winsauer, S.A. and Underwood, J.N. 1980. Computer Simulation of Forest Harvesting System, Development, and Application. *Transactions of the American Society of Agricultural Engineers* 23(2), pp. 317–323.

Zhang, S. et al. 2009. Impact of precommercial thinning on tree growth, lumber recovery and lumber quality in Abies balsamea. *Scandinavian Journal of Forest Research* 24(5), pp. 425–433. Available at: http://www.tandfonline.com/doi/abs/10.1080/02827580903124392 [Accessed: 4 February 2013].

Zhang, S.Y. et al. 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), pp. 945–952. Available at: http://www.nrcresearchpress.com/doi/abs/10.1139/x05-307 [Accessed: 21 August 2013].

APPENDIX:

ADDITIONAL SITE AND STAND INFORMATION FOR CTRN PLOTS USED IN CHAPTER 4

The next few pages show detailed information for each treatment plot at each study site. In contrast to the tables and figures shown in Chapter 4, which show aggregated treatment data, the tables and figures in this appendix show the individual plot level data for each study site.

Table A.1: Site and treatment information for six CTRN sites as measured in 2012**.**

Site Name	Treatment Removal (%)	Treatment Delay (yrs)	Age (yrs)	PCT	TPH	QMD (cm)	BA ($m^2 \cdot ha^{-1}$)	Height (m)
Alder Stream								
	33	0	45	1984	905	21.3	32.3	15.5
	33	5	45	1984	744	21.8	27.8	16.5
	33	10	45	1984	756	21.5	27.4	16.6
	50	0	45	1984	583	21.5	21.2	13.2
	50	5	45	1984	446	22.2	17.4	15.1
	50	10	45	1984	484	20.8	16.4	15.1
	control	-	45	1984	1612	18.5	43.2	14.8
Lake Macwahoc								
	33	0	54	1983	694	23.0	28.9	16.6
	33	5	54	1983	670	18.4	17.9	15.0
	33	10	54	1983	918	18.4	24.4	16.0
	50	0	54	1983	546	23.3	23.2	16.5
	50	5	54	1983	446	18.6	12.2	14.9
	50	10	54	1983	384	21.7	14.2	16.4
	control	-	54	1983	1686	18.7	46.5	16.5
Lazy Tom								
	33	0	43	1984	843	20.6	28.1	12.1
	33	5	43	1984	930	18.9	26.1	14.0
	33	10	43	1984	1017	17.4	24.1	12.8
	50	0	43	1984	583	23.0	24.2	13.2
	50	5	43	1984	533	20.4	17.5	14.3
	50	10	43	1984	657	18.1	16.9	13.1
	control	-	43	1984	1674	17.4	39.6	13.1
PEF Comp. 23 A								
	33	0	52	1983	818	20.8	27.9	14.1
	33	5	52	1983	880	19.5	26.2	14.8
	33	10	52	1983	856	17.8	21.4	14.4
	50	0	52	1983	670	20.8	22.7	13.8
	50	5	52	1983	645	18.8	17.9	13.1
	50	10	52	1983	657	16.5	14.1	12.9
	control	-	52	1983	2046	15.4	37.9	14.0
Ronco Cove								
	33	0	35	1985	1004	20.3	32.5	14.8
	33	5	35	1985	992	19.7	30.2	14.9
	33	10	35	1985	1290	17.2	29.9	14.8
	50	0	35	1985	769	23.0	32.0	14.7
	50	5	35	1985	521	22.5	20.8	14.8
	50	10	35	1985	620	19.5	18.5	15.9
	control	-	35	1985	1947	17.4	46.3	14.8
Weeks Brook								
	33	0	42	1985	1141	19.1	32.6	14.8
	33	5	42	1985	1141	18.4	30.2	14.8
	33	10	42	1985	1066	17.4	25.3	15.1
	50	0	42	1985	682	21.8	25.4	14.8
	50	5	42	1985	670	21.1	23.4	14.7
	50	10	42	1985	744	18.4	19.7	15.1
	control	-	42	1985	2046	16.6	44.0	14.3

Notes: PCT = precommercial thinning; TPH = trees per hectare; QMD = quadratic mean diameter;

BA = basal area

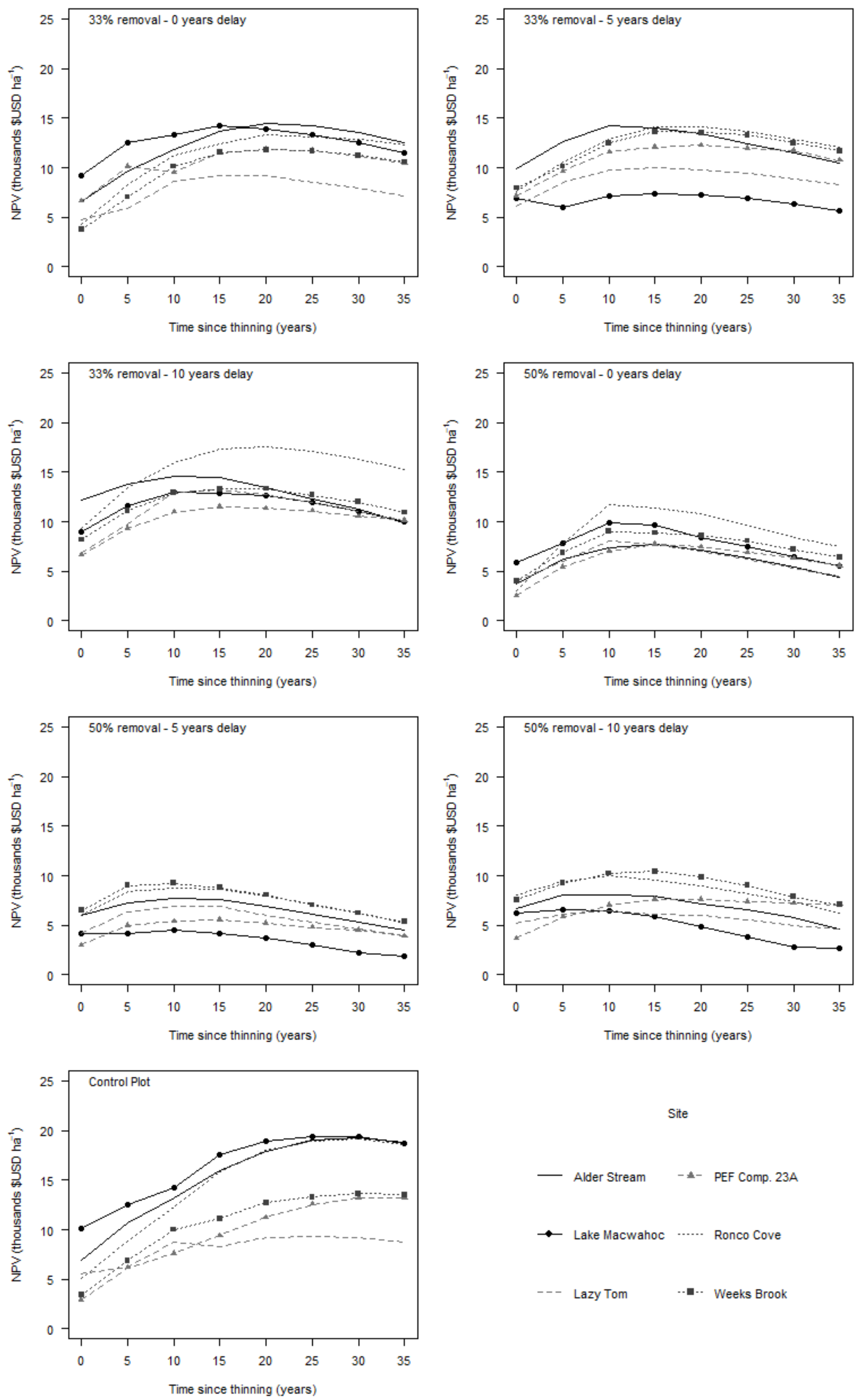

Figure A.1: Net present value for all study sites and treatments.

BIOGRAPHY OF THE AUTHOR

Patrick Hiesl was born in Laupheim, Germany, on May 30, 1984. He was raised in southern Germany and graduated from Karl-Arnold vocational high school in Biberach a.d. Riss in 2005. He attended the University of Applied Forest Sciences in Rottenburg, Germany, and graduated with a Bachelor's degree in Forest Management in 2010. After working as an office manager at a small company in southern Germany he moved to Maine in the spring of 2011 to work as a forest technician crew leader for the Cooperative Forestry Research Unit. In the summer of 2011 he entered the Forest Resources graduate program at the University of Maine. After receiving his Master's degree in Forest Resources in 2013 he enrolled in the Doctor of Philosophy program in Forest Resources. Patrick published his research in several peer-reviewed journals and presented at local and national meetings. Since 2011 he is a member of the Society of American Foresters. Patrick is a candidate for the Doctor of Philosophy degree in Forest Resources from the University of Maine in August 2015.