ASSESSING THE POTENTIAL IMPACTS OF FOREST MANAGEMENT PRACTICES ON WILDLIFE HABITAT, CARBON SEQUESTRATION, AND TIMBER HARVESTING IN COASTAL BRITISH COLUMBIA

by

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ABSTRACT

The forests of coastal British Columbia are some of the most productive in the world, providing a wide range of values including timber production, carbon sequestration, and wildlife habitat. Forest management often requires weighing competing values and implementing decisions to promote them, while avoiding negative impacts to other values. Forest ecosystems models such as FORECAST and Habitat Suitability Indices provide a means of analyzing alternative management strategies for their impacts on multiple values, and serve as a tool for informing adaptive management decisions. The objectives of this thesis were to model and assess the impacts of different forest management practices on wildlife habitat, carbon storage, and timber harvesting in coastal British Columbia.

This analysis consisted of a number of alternative harvesting prescriptions, including clearcut harvesting and low intensity thinning treatments. Each treatment was quantified on its ability to simultaneously generate timber, carbon and habitat value. Results of the study suggest that extension of rotation periods between harvest treatments can provide gains in all three values over shorter rotations. Low intensity thinning treatments can also be applied to further promote habitat value with only minor reductions in carbons stocks. In addition, thinning treatments can decrease the time required to develop high quality habitat over that of either unmanaged or clearcut management. If selectively applied over a landscape scale, these management prescriptions could be used to provide a range of forest values and address a variety of resource demands.

PREFACE

This thesis is original, unpublished, independent work by the author, G. McLaughlin.

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LIST OF ABBREVIATIONS

BC:	“British Columbia”
C:	“Carbon”
DBH:	“Diameter at breast height”
HSI:	“Habitat Suitability Index“
LU:	“Landscape unit:
NOGO:	“Northern Goshawk”
PNW:	“Pacific Northwest”
SPH:	“Stems per hectare”

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To my family

1 INTRODUCTION

1.1 Forest management for multiple objectives

Forests produce a wide variety of values with both natural and human benefits, including timber, recreation, wildlife habitat, biodiversity, water quality and sequestration of carbon dioxide. The task of forest management involves modifying forest ecosystems and the interactions within them in order to generate desired values (Bunnell and Dunsworth 2009). Management often requires weighing each of these values, which sometimes compete, and prioritizing key values based on natural and social demands, while avoiding negative impacts on other values. Further complicating this issue is the fact that forests are complex and dynamic systems, often with abundant species. Forest managers also must deal with changing societal demands of values, heightened, often conflicting responsibility for sustaining these values, and long time frames over which to work (Bunnell and Dunsworth 2009). The summation of these complexities make forest management a difficult task.

Coastal British Columbia (BC) contains some of the most productive forested areas in the world and provides a wide range of values. Historically, BC has been among the world's leaders in production of high quality wood products, with the forest industry an important aspect of BC's economy. At the same time, forest types and site conditions within coastal BC allow for significant sequestration of atmospheric carbon, providing an important tool in climate change mitigation. Finally, BC's coastal forests naturally contain large trees and structural complexity that provide habitat to over 380 different terrestrial vertebrate species (Bunnell 1995). Many of which have been significantly impacted by historical forest management. This includes the Northern Goshawk (*Accipiter gentilis*), an endangered species that has been of management concern in western North America for over 20 years.

1.2 Forest models in adaptive management

Forest values are impacted by management practices in different ways. Therefore, management that aims to address a diverse array of forest values can be complex, given potential complementary and adverse impacts resulting from different treatment types. Forestry models provide land managers with a means of simulating simplified and conceptual representations of reality, in order to analyze and project alternative management strategies. Modeling studies provide an interface between experience-based and scientific knowledge and serve as a means of learning and research before applying adaptive management (Wolfslehner and Seidl 2010). They can be invaluable in informing management decisions.

1.3 Thesis overview

A number of recent studies have tried to quantify the effects of forest management on carbon stocks and carbon sequestration in forests around the world. Habitat impacts from forest management has also be extensively studied within BC and elsewhere. However, little research has been done to quantify both of these values simultaneously and observe potential complementary benefits and trade-offs. I am unaware of any such modeling study that has been done in coastal BC on this topic.

The purpose of this thesis is to study the potential of forest management practices applied in coastal BC on the generation of multiple resource objectives; namely timber, carbon sequestration and wildlife habitat. Through the use of ecosystem and ecological habitat models, this study will identify the effects on these values of alternative silvicultural treatments, including thinning. This study will also identify a modeling approach to quantify these values, and use this approach to identify complementary benefits and trade-offs between them.

1.3.1 Research objectives

The purpose of this thesis is to:

- Model and assess the impacts of different forest management practices on wildlife habitat, carbon sequestration and storage, and timber harvesting in coastal British Columbia.

This thesis is sectioned into six chapters. Chapter 1 provides an introduction and overview of the study. Chapter 2 provides information on the management of the Northern Goshawk, an indicator species of mature forest ecosystems in BC. The review includes stand attributes important for nesting habitat, as well as investigates potential alternative strategies for promoting new habitat areas. Chapter 3 includes a review of existing knowledge of how forest management and alternative management strategies like thinning impacts carbon sequestration and timber harvesting. Chapter 4 explains the methods used in the modeling study conducted, including a description of the models, modeling approach, data and assumptions. Chapter 5 presents the results (data outputs and quantified results) and discussion (expansion and implications of modeling results, limitations, and further study) from the study. Finally, Chapter 6 summarizes conclusions of the study.

2 REVIEW OF NORTHERN GOSHAWK IN BRITISH COLUMBIA

2.1 Introduction and chapter overview

The Northern Goshawk (*Accipiter gentilis*) is an endangered species in the Pacific Northwest (PNW) that has been of management concern in western North American for the past 20 year (Squires and Kennedy 2006). Given their habitat requirements of old growth stand structure, Northern Goshawks are often considered indicator species of mature forest types that provide habitat to a range of other species (Northern Goshawk Recovery Team 2008). Loss of habitat has been identified as the primary factor threatening populations of Northern Goshawk in British Columbia (BC) (Stuart-Smith el at. 2012). Population numbers for the *A. gentilis laingi* subspecies in BC are limited (Doyle 2006), but are estimated at less than 1,000 individuals (Manning and Chytyk 2005). Alarmingly, this small population is estimated to comprise nearly 50% of the global population of *A. gentilis laingi*, as well as 100% of the Canadian population (Mahon 2009). *A. gentilis laingi* in BC is limited to a few regions of Vancouver Island, Haida Gwaii and other coastal areas. Because of small population numbers and reduced habitat areas, the Northern Goshawk[1] has been a listed a "Threatened" species under the Committee on the Status of Endangered Wildlife in Canada since 2000, as well as a Species at Risk under the BC Forest Range and Practices Act.

Given the tenuous populations of Northern Goshawk and other species dependent on mature forest types, as well the potential for further influences caused by timber harvesting, it is important to better understand the detailed impacts of forest management on wildlife habitat. This chapter consists of a literature review, conducted to examine the existing knowledge on Northern Goshawk habitat in BC. This chapter will provide a short description of management of Northern Goshawks in BC, as well as determine what structural variables are important to identifying quality habitat and assess how timber management can impact goshawk nesting habitat.

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[1] Reference to "Northern Goshawk" within this document refers specifically to the coastal (*A. gentilis laingi*) Northern Goshawk subspecies

2.2 Species description

The Northern Goshawk is a raven-size (55-61 cm in length) raptor with short, rounded wings and a long tail, making it a powerful flyer capable of direct pursuit hunting (Northern Goshawk Recovery Team 2008). Adults have a bluish-gray back, a white chest with gray barring, white eye-stripes separating their black crown from their back, a barred tail and large white under-tail coverts. Immatures are overall brown in color with white eye-stripes and buff-colored chests with dark brown verticals streaks. Goshawks are well adapted for forest habitats, having short, round wings and long tails that make them capable of quick maneuvering within the forest canopy. They are effective direct pursuit hunters, primarily preying on a variety of small mammals, passerines, and hares (Squires and Reynolds 1997). Coastal BC goshawks primarily feed on red squirrels, grouse, and snowshoe hares, as well as forest birds such as thrushes, jays and woodpeckers, many of which are associated with low shrub layers under the canopy (Mahon 2009).

2.3 Status of Northern Goshawk in British Columbia

The Northern Goshawk Recovery Team (2008) estimated between 352 and 374 breeding pairs within Canada (all in BC), as well as an additional 309 to 384 pairs in Southeast Alaska and Washington. Estimates of current and historic populations are imprecise due to the difficulty of measuring and monitoring the bird's survival and recruitment. Monitoring is also difficult because of low detection rates, high annual variability in occupancy, and large distances between alternative nests (Northern Goshawk Recovery Team 2008). Instead, these estimates have been developed from the number of existing pairs living in suitable habitats.

In BC, the two major threats to populations of goshawks are harvesting of old growth stands and conversion to earlier seral stages, causing habitat loss and habitat fragmentation (Northern Goshawk Recovery Team 2008; Mahon 2009). The increase in industrialized forest harvesting has resulted in a reduction in available goshawk habitat. It is estimated that 50-60% of the global habitat area of Northern Goshawk occurs within Canada/BC (Northern Goshawk Recovery Team 2008). The advent of modern forest technology has allowed harvesting to occur on a larger scale throughout coastal BC, resulting in an accelerated rate of conversion of old growth stands to second growth. As a result, *A. gentilis laingi* was classified as "Identified Wildlife Species" under the Forest Practices Code Act of British Columbia and is listed as "Species at Risk" under the BC *Wildlife Act*. With the later enactment of the Forest and Ranges Practices Act, *A. gentilis laingi* remained in a category of Species at Risk, qualifying it as potentially affected by forest management on Crown land.

2.4 Northern goshawk habitat

2.4.1 Habitat loss through forest management

Northern Goshawk has been widely accepted as a species that is sensitive to forest development (Reynolds et al. 1992; Squires and Kennedy 2006). It is thought that its population distribution has been impacted by harvesting of mature and old growth forests and conversion to earlier seral stages (Mahon and Doyle 2005; Stuart-Smith el at. 2012; Mahon 2009; Kennedy 2003). This habitat loss affects population numbers by reducing the availability of nests, constraining dispersal of immature birds, increasing risk of depredation, reducing gene flow among populations, reducing available prey abundance, increasing inter-species competition and increasing human-caused disturbances and interactions (Kennedy 2003). As these impacts of logging have occurred fairly recently, their overall long term impacts on goshawk populations remain unclear (Northern Goshawk Recovery Team 2008).

2.4.2 Stand structure characteristics

Throughout North America, the Northern Goshawks live in a wide variety of forest types and successional stages. In BC, habitat primarily consists of coniferous forests of Douglas-fir, western hemlock, lodgepole pine, ponderosa pine, and various spruce species (Northern Goshawk Recovery Team 2008; Mahon 2009). Some researchers hypothesize, however, that given the wide geographical range of habitat areas, goshawks may respond more to structural attributes than to specific species compositions (McGrath et al. 2003). At a regional scale, goshawks are considered habitat generalists, but at finer scales, their habitat requirements are more specific (Squires and Reynolds 1997). While specific stand qualities deemed important for goshawk habitat vary between studies, a number of structural characteristic are consistently included. These include mature to old-growth stand types with large trees (height and diameter), as well as high canopy closure (Cooper and Stevens 2000; Northern Goshawk Recovery Team 2008; Mahon 2009).

2.4.2.1 Mature forest (age):

Northern Goshawks have occasionally been known to nest in young, even-aged coniferous stands but typically they choose mature and old growth forests with large trees and high canopy closure (Cooper and Stevens 2000). It is believed that this behavior reflects their need for strong branches suitable for building a nest, along with dense surrounding forest for providing protection from predators and weather (McClaren et al. 2005). As mature structural characteristics can occur during a range of stand ages, optimum stand ages for goshawk habitat found in literature vary significantly. Nesting success in BC has been observed to be higher in forested areas containing higher percentages of mature and old growth forests (> 80 years old) (Stuart-Smith el at. 2012). In the North Coast region and on Haida Gwaii, nesting habitat is often observed in stands of 80 to 120 years of age, while on Vancouver Island and in the South Coast region, nesting habitat can occur in earlier ages of 40-100 years old (Northern Goshawk Recovery Team 2008). Nests were also observed on Vancouver Island in 60-80 year old second growth stands, and these stands showed suitable habitat structure as early as 50 years old (McClaren et al. 2003). In Washington, a few nests were observed in 40-54 year old second growth stands, though the average tree size in these stands was significantly larger than the surrounding forest (highly productive sites) (Bosakowski et al. 1999).

It has also been demonstrated that Northern Goshawk habitat requirements are less a factor of stand age or species composition and more associated to stand structural characteristic (Northern Goshawk Recovery Team 2008; Finn et al. 2002), as structural maturity of a stand and the trees within it have been said to form the basis of goshawk habitat (Mahon et al. 2003).

2.4.2.2 Large trees (height and diameter)

Research of goshawk habitat consistently shows that goshawks will nest in larger trees within a stand, and within stands of larger trees than the surrounding area (Cooper and Stevens 2000; Penteriani 2002). Nest trees on the BC coast are often large (>50 cm diameter at breast height, DBH) with dominant or co-dominant canopies >28 m in height (Northern Goshawk Recovery Team 2008). Tall, large diameter trees with large branches are needed to support and provide protection of the large stick nests used by goshawks (Stuart-Smith el at. 2012).

2.4.2.3 Canopy closure

Mid to high levels of canopy closure have been consistently identified as a common characteristic within North American goshawk nesting habitat (Squires and Reynolds 1997; Cooper and Stevens 2000; Mahon 2009; Stuart-Smith el at. 2012). It is thought that high canopy closure may benefit goshawks in two primary ways: protection and hunting flyways. Dense canopies provide protection for goshawk nests, which are typically built just below the canopy layer on thick branches (Squires and Kennedy 2006). In addition, denser canopies typically result in more open understories, which is important for prey abundance and open flyways for hunting (Cooper and Stevens 2000).

Canopy closure of studied nesting sites varies, but is typically >50% (Kennedy 2003, Greenwald et al. 2005), ranging from 56%-85% (Finn et al. 2002; Kennedy 2003; Mahon and Doyle 2005). Bluxton 2002 also found that >96% of goshawk kill sites were located in >60% canopy closure within a study in western Washington.

2.5 Forest management and goshawk habitat

Northern Goshawk is widely accepted as being sensitive to timber harvest across North America (Reynolds et al. 1992; Squires and Reynolds 1997; North Goshawk Recovery Team 2008). Overall tolerance of goshawks to nearby harvesting is dependent on regional types of prey and their associated habitat requirements, local and nearby nesting habitat availability, and abundance of competition and predators in the area (Stuart-Smith el at. 2012). Goshawks have also been shown to display strong levels of fidelity, making them resistant to leaving established nests in the absence of severe habitat degradation (Mahon 2009; Saga and Selas 2012; Peteriani and Faivre 2001). Reuse of unoccupied nests has also been observed

(Saga and Selas 2012). BC studies have also identified heavier logging intensity (greater percentage of trees removed from a stand) as having negative impacts on nest reoccupancy post-harvesting (Mahon and Doyle 2005; Mahon 2009).

A few recent studies have suggested that goshawks are relatively tolerant to nearby harvesting. Mahon 2009 conducted harvesting trials near known goshawk nesting sites in west-central BC and found no negative impacts of timber harvesting on re-occupancy or fledgling production rates. Some fine scale movement of nests away from logging was observed. Peteriani and Faivre 2001 found similar results in Europe with goshawks continuing to occupy nests after partial harvesting of up to 30% basal area removal. Beyond 30%, goshawks relocated to nearby unharvested stands with no negative impacts on breeding or reproductive rates (Penteriani & Faivre, 2001). In Norway, Saga and Selas 2012 observed no significant effects of timber harvesting within 50 meters of nests in southeastern pine and spruce forests as well. They did notice effects of tree species composition on nest re-use, and recommend maintenance of at least two hectares (ha) of mature forest surrounding known nests (Saga and Selas 2012). These studies suggest that goshawks may be more tolerant of lower impact timber harvesting if management protects the larger areas surrounding nests.

2.5.1 Thinning for Northern Goshawk habitat

Some studies in the PNW have looked at potential opportunities to utilize forest management techniques in order to promote stand attributes and structural diversity for suitable bird habitat (Cahell 2013; Ahlering and Faaborg 2009; Finn et al. 2002). Thinning treatments can reduce competition among residual trees and cause an increase in growth, size, branch diameter and crown size (Oliver and Larson 1996). Specifically regarding goshawk habitat, Finn et al. 2002 recommended utilizing silvicultural prescriptions to promote suitable hunting and nesting habitat in younger PNW conifer stands. In this study, a single moderate-intensity thinning treatment was recommended in order to promote certain stand structural characteristics that are beneficial to goshawks (Finn et al. 2002). Within 5-10 years of thinning, this approach was thought to yield deep forest canopies and low shrub cover, characteristics found to be beneficial for nesting habitat

(Finn et al. 2002). Studies have also suggested this approach could be used to promote hunting habitat with a low intensity thinning, removing smaller trees and opening the understory for flyways (Finn et al 2002; Bloxton 2002).

2.6 Summary

The Northern Goshawk is a species of management concern that has been historically impacted by forest management and associated reduction of old growth/mature forested area in BC. Quality habitat area has been shown to be less a factor of stand age and more depended on key stand structural variables, including tree height, tree diameter, and canopy closure. As these structural attributes can be manipulated through silvicultural prescriptions such as thinning, there may be a potential to promote high quality goshawk habitat area through forest management practices.

3 FORESTS MANAGEMENT, CARBON AND TIMBER HARVESTED

3.1 Introduction and chapter overview

On a global scale, more carbon is stored within forest ecosystems than any other terrestrial pool or the atmosphere (Natural Resource Canada 2007, as cited in Greig and Bull 2009). Recent research has shown that over the past 10 to 15 years, North American forests have been a net carbon sink, sequestering 270 +/- 130 million tons of carbon per year (Woodbury et al. 2007; Birdsey 2007). Because of this, the International Panel on Climate Change has concluded that "a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit" (as cited in Kurz et al. 2008).

Carbon storage within forests ecosystems is highly dynamic, determined by a balance of inputs via photosynthesis growth and releases by respiration and forest disturbance (Kurz et al. 2008). These processes are affected by a number of natural interactions such as changes in forest cover, nutrient and water cycling, soil composition and natural disturbances (FAO 2005). Ties have also been made between human land-use history and historical forest carbon fluxes within forests (Houghton 1999). This potential of human influence emphasizes the need to better understand the impacts of forest management on ecosystem carbon storage.

Different forest management strategies can also impact long term timber production. Rotation ages in traditional industrial forestry are chosen in order to maximize annual production. Changes in the time between harvesting therefore have impacts on overall volume harvested. Also, alternative treatments such as thinning can use applied to increase volume growth per area or recover anticipated mortality within a stand (Oliver and Larson 1996).

This chapter will review the studied impacts on carbon inventories and timber harvesting of forest management prescriptions, specifically, thinning treatments as described in Chapter 2.

3.2 Impacts of forest management on forest carbon

Timber harvesting impacts forest carbon dynamics within a stand by removing biomass in the form of wood products, transferring carbon between various ecosystem pools (i.e. litter and deadwood debris), and influencing overall carbon stock balance. Harvest treatment characteristics such as harvest intensity and harvest frequency have been demonstrated to have effects on forest carbon stocks in a variety of forest types (Nunery and Keeton 2010; Harmon et al. 2009; Smithwick et al. 2007). In general, longer time periods between disturbance events and lower intensity disturbance types result in greater long-term carbon stocks (Harmon et al. 2009; Smithwick et al. 2007; Harmon and Marks 2002). This has been demonstrated in a number of modeling studies where extending periods between clearcutting resulted in higher levels of stored carbon (Harmon et al. 2009; Harmon and Marks 2002; Seely et al. 2002). Other aspects of management such as site preparation, planting, and stand tending have also shown impacts on carbon stocks and overall carbon balance (Kurz et al. 2002). Manipulation of stand structure, species composition and stand density through various harvesting strategies can produce a range of carbon impacts as well.

3.2.1 Thinning treatments

Chapter 2 identified thinning treatments as potentially improving Northern Goshawk habitat benefits. In utilizing thinnings, managers can maintain a desired level of stand density and the growth potential associated with that density. While thinning has been demonstrated to have impacts on stand development and timber production in the PNW (Davis 2007; Curtis and Marshal 2009; Pitt and Lanteigne 2008; Roberts et al. 2008; Sprugel et al. 2009), overall impacts on forest carbon stocks less understood. In general, thinning treatments remove trees and free up growing space for the residual trees. These overstory trees then refill the newly available growing space with crown expansion, further root development and faster growth rates (Oliver and Larson 1996). However, a wide variety of results have been observed among the carbon studies that do exist. Of the existing studies, overall impacts of thinning have been:

- Positive on long-term ecosystem carbon stocks on Appalachian spruce-fir (Moore 2012) and poplar stands (Keyser 2012);
- Of little significant difference when compared with a no-harvest scenario in Appalachian hardwoods (Hoover and Stout 2007), Minnesota pine plantations (Powers 2012), and Sierra Nevada mixed-conifer stands (Hurteau and North 2009);
- Negative impacts in both western coniferous (Clark et al 2011; Finkral and Evans 2008; Campbell et al. 2009) and eastern (Chiang et al. 2008, Keyser 2010, D'Amato 2011, Powers 2011) North American forests.

While overall impacts of thinning treatments on forests carbon vary between studies, a number of component impacts have consistently been reported between studies, including effects on stand growth and sequestration rates, with thinned stands showing either similar (Hoover and Stout 2007; Makinen and Isomaki 2009) or increased (D'Amato 2011; Moore 2012; Keyser 2012) long term growth/sequestration rates than untreated. Studies have also described the overall impacts of thinning treatments on carbon stocks as a result of various factors including timing of thinning (Keyser 2012), intensity of thinning (Makinen and Isomaki 2009; Curtis and Marshal 2009) and distribution of thinned stems (Hoover and Stout 2007; D'Amato 2011). Keyser 2012 found that younger Appalachian mixed-hardwood stands showed more positive response to thinning treatments and were better able to recover lost carbon stocks through increase growth rates than more mature stands.

Thinning intensity has consistently been observed to impact forest carbon stocks, with lower intensity thinning treatments (maintaining a large portion of mature trees) resulting in greater stored carbon stocks than heavier thinning treatments (Harmon et al. 2009; Keyser 2010; Nunery and Keeton 2010). A number of studies on impacts of fuel reduction thinnings have shown that if thinning treatments are too heavy, long-term stand volume can be reduced, even if individual stem growth rates have increased (Clark et al. 2011; Makinen and Isomaki 2009; Curtis and Marshal 2009).

Variance in tree size classes removed in thinning treatments has also been found to have impacts on resulting carbon stocks post-treatment. D'Amato 2011 found that "thin from below" treatments (removing smaller size class trees) resulted in greater total carbon storage in eastern red pine plantations, due to the higher proportion of larger residual trees. Hoover and Stout 2007 observed no significant different in carbon stocks density between “thin from below” and “CONTROL” scenarios in Allegheny hardwood stands. Conversely, “thin from above” scenarios (removing larger size classes) resulted in lower total carbon stocks, but higher carbon growth increment in the year following thinning (Hoover and Stout 2007).

Forest management treatments such as thinning can be utilized in order to max volume growth within a stand. Overall impacts of thinning depends similar factors those described around carbon impacts: 1) appropriate timing of thinning; 2) removal of least vigorous tree 3); spacing between residual trees (Oliver and Larson 1996).

3.3 Summary

The potential impacts of management prescriptions such as thinning are still somewhat inconclusive, as demonstrated by the amount of variance between studies. However, a number of key components of thinning prescriptions have been identified as potentially impacting on carbon results, including thinning intensity, timing of thinning treatments, and size classes removed.

4 CASE STUDY

4.1 Description of study area

The project area is located 160 km north of Vancouver, BC Canada, within the Toba River watershed. Forests within this region are predominantly classified as the Pacific Ranges Ecoregion, with maritime climate conditions consisting of warm, dry summers and mild, wet winters. There are five Biogeoclimatic (BEC) zones and eight subzones or variants existing within the project area, from which the Coastal Western Hemlock (CWHvm1) subzone was selected for this modeling study. Commercial tree species within Toba region primarily include Douglas-fir (*Pseudotsuga menziesii*, abbreviated *Fd*), western red cedar (*Thuja plicata, Cw*), and western hemlock (*Tsuga heterophylla, Hw*) (Smart 2010).

While the Toba watershed includes a large diversity of wildlife resources, primary management concern includes Grizzly Bear, Marbled Murrelet, Mountain Goats, Roosevelt Elk, deer and fish (Smart 2010), with Northern Goshawk not specifically addressed within the landscape unit planning. However, surveys completed in 2007 identified 23,318 ha of moderately to highly suitable habitat area within the Toba region and confirmed the existence of goshawks in the landscape unit (Keystone Wildlife Research Ltd. 2008). Goshawks have also been identified as susceptible to potential habitat disturbance within the area (Keystone Wildlife Research Ltd. 2008).

4.2 Methods

Increased awareness of both regional and global stakeholders requires managers to understand and demonstrate the potential impacts of their management decisions on a variety of resource values (Seely et al. 2004). As forest managers consider multiple resource objectives, the need is clear for tools capable of credibly forecasting impacts of alternative management strategies (Kimmins et al. 1999). Several such models have been developed, allowing managers to have a better understanding of ecosystem responses to various management activities. These models also allow managers to simulate potential hypotheses surrounding management strategies and analyze trade-off scenarios by providing a simplified, conceptual representation of reality. However, models for natural systems are not “closed” and therefore results must be scrutinized for what they are.

4.2.1 Quantifying carbon and timber: FORECAST

FORECAST is a stand-level forest growth and ecosystem dynamics simulator, created to provide a tool for observing the impacts of harvesting, silvicultural treatments, and natural disturbances on site productivity, stand dynamics, and other non-timber values (Kimmins et al. 1999). FORECAST uses a “hybrid” approach, relating “biologically active” biomass components (foliage and small roots) with calculations of primary production, nutrient uptake, and light capture, creating modeled growth potentials for various components of a forested ecosystem. Rates are created from a combination of historical data (yield curves, stand density, etc.) and researched biophysical processes (decomposition rates, photosynthetic saturation curves, etc.) (Seely et al. 2002). Growth potentials are then compared with modeled nutrient and light availability to simulate ecosystem dynamics.

FORECAST is a stand-level model that includes a number of sub-models which disaggregate stand level information into stem-level data, used to generate structural variables over time (Kimmins et al. 2010). These variables are important for modeling potential wildlife habitat suitability, which requires explicit representation of structural features deemed important habitat characteristics of the species in question. This includes individual tree measure such as height/diameter, stand structural information related to seral stages (Bunnell and Dunsworth 2009), habitat structures like snags and deadwood, as well as the processes that lead to the formation of the features (i.e. density dependent mortality, non-stand replacing disturbances, harvesting events, snag fall, and organic matter decomposition). FORECAST includes stem-level data such as top height and DBH calculated for each live stem, crown height and light penetration through the canopy, snag count, as well as gross and merchantable volume estimates. These outputs make it well suited for multi-objective studies. FORECAST has been used in a number of similar modeling studies throughout Canada, including management impacts on carbon in boreal forest ecosystem (Seely et al 2002; Jie et al 2011), tradeoffs within multi-objective forest management strategies in northeastern BC (Seely et al 2004), and stand structural characteristic in coastal coniferous BC forests (Kimmins et al. 2008; Gerzon et al. 2011). A detailed description of the model is available in Kimmins et al. 1999 and Kimmins et al. 2010.

While FORECAST is well suited for this study, it does have two limitations. First, the growth rate of individual stems within the model is limited by light availability and belowground nitrogen, and does not consider other factors such as moisture or temperature limitations that may also impact growth rate (Seely et al. 2002). These other limitations are assumed to be accounted for within the growth and yield data used to calibrate the model (Seely et al. 2002). Second, growth rates within the model are assumed to be constant between rotations, and therefore do not account for long-term changes that may result from climate change (Seely et al. 2002).

4.2.2 Quantifying goshawk habitat: Habitat Suitability Index

To quantify the impacts of management on goshawk habitat, a habitat suitability index (HSI) was used in tandem with FORECAST. The underlying assumption of HSI models is that habitat characteristics are an important factor in species distribution and abundance (Schamberger et al. 1982). The HSI concept uses a numerical index (often from 0 - 1) that represents the capacity of a given area to provide suitable habitat for a specific species. Point values are assigned to key environmental variables in relation to their ability to support an identified species. The combined score of all of the key variables provides an overall suitability score for the area in question.

HSI's are commonly used in conducting habitat assessments and have been successfully implemented in several goshawk habitat mapping and supply analyses in BC (Manning et al. 2002; Mahon et al. 2003; Rumsey et al. 2004; Marquis et al. 2005; Mahon et al. 2008; Keystone Wildlife Research Ltd. (2008); see review of others by Mahon 2005). As with other types of models, HSI's must be carefully selected to best represent the area and species of interest. A number of HSI's have been developed for the Northern Goshawk, including two for coastal BC and one specifically for Toba Inlet. All three models used a similar methodology, rating systems and multiplicative, non-compensatory equations (meaning one variable cannot make up for a deficiency of another: for an area to be considered a "High" suitability habitat in these models, it must contain high values of all component habitat variables). However, the models differed in selection of habitat variables and assigned habitat value ratings. Appendix A provides a table of included variables by study.

The HSI used in this study is based on a model developed by Keystone Wildlife Research Ltd. in a terrestrial wildlife and vegetation study of the Upper Toba Valley (Keystone Wildlife Research Ltd. 2008). This model was chosen for this thesis due to its applicability to the project area and adaptability to available modeling output variables. The Keystone model incorporates variables and associated ratings from both the Marquis et al. 2005 and Rumsey et al. 2004 models (both developed for coastal BC), adapted to best suit the habitats and data availability present in the Toba region. Key variables selected for this study include stand height, stand age, canopy closure, tree species, and average DBH (see Equation 1).

FIGURE 1: HABITAT SUITABILITY INDEX FORMULA (ADAPTED FROM KEYSTONE WILDLIFE RESEARCH LTD. 2008)

$$Habitat\ Suitability\ Rating = \left(\frac{(Stand\ Height\ Rating + Stand\ Age\ Rating)}{2}\right) * Canopy\ Closure\ Rating * Tree\ Species\ Rating * DBH\ Rating$$

While stand age and stand height often correlate closely, there can be instances where they vary, thus requiring both variables within the HSI. For instance, highly productive sites can achieve taller average heights and moderate habitat suitability at younger ages, while lower productive sites may have the opposite, even at older ages. In order to avoid effects of correlation between the variables, the Keystone Wildlife Research Ltd. (2008) uses an average HSI rating of age and height, shown in Figure 1.

In addition to the variables listed in the Keystone Wildlife Research Ltd. (2008) HSI, an average stand diameter at breast-height (DBH) variable was added to the formula. Stand DBH is commonly associated with goshawk studies, but not often included in HSI models due to inventory data availability. DBH rating classes were adapted from classes identified in a proposed *A. gentilis laingi* habitat area study conducted in the Central Coast of BC (Mitchell et al. 2008) and confirmed with a Toba Inlet regional forester (personal communication with Brian Smart RPF September 2013).

The overall rating for tree species composition is determined as a sum of the component species ratings, multiplied by the percent composition. For example, a stand that is 60% Douglas-fir (Fd) and 40% western red cedar (Cw) would receive a rating: Fd(60%) * 1 + Cw(40%) * 0.5 = (0.6) + (0.2) = 0.7.

TABLE 1: STAND AGE HSI RATINGS

Age	Rating
0-40	-
41-80	0.50
81-140	0.75
140+	1.00

TABLE 2: STAND HEIGHT HSI RATINGS

Height (m)	Rating
0 - 10.4	0.10
10.5 - 19.4	0.25
19.5 - 28.4	0.80
>28.4	1.00

TABLE 3: TREE SPECIES HSI RATING

Tree Species	Rating
Cw	0.5
Fd	1.0
Hw	1.0

TABLE 4: DBH HSI RATINGS

DBH (cm)	Rating
<25	-
26-34	0.50
35-50	0.75
>50	1.00

TABLE 5: CANOPY CLOSURE HSI RATINGS

Percent Closure	Rating
1-15%	-
16-25%	0.2
26-35%	0.4
36-45%	0.6
46-55%	0.8
56-85%	1.0
86-100%	0.8

4.2.3 Modeling process and scenarios

Modeling consisted of stand-level simulations within FORECAST, followed by processing output data and transferring habitat variables into the HSI model (Microsoft Excel). Quantified carbon pools are include: live tree biomass (includes bole, branches, etc.), deadwood biomass (standing and lying deadwood), litter biomass and wood product storage. The wood products pool was calculated with harvested volume outputs from FORECAST and a decay formula taken from Clark et al. 2011 ("simple decay" formula). Rate of decays was estimated based on half-life values of various wood products (Skog and Nicholson 2000). Rather than estimate the product type distribution from each harvest and associated half-life, a conservative estimate of 20 years was used for all harvested volume. Soil pools were excluded from the ecosystem totals.

A total of five modeling scenarios (shown in Table 6) were developed to test the impacts of harvesting and thinning treatments on carbon stocks, goshawk habitat, and timber production. One scenario consisted of an unmanaged scenario (CONTROL), where no thinning or harvest treatments were applied for the full modeling period. This scenario was included because old growth stands have been associated with high levels of carbon stocks (Harmon et al. 1990) and high goshawk habitat value (Cooper and Stevens 2000). Two unthinned clearcut-harvesting scenarios were created to represent common practice harvesting within Toba Inlet: a Baseline High (BASE1) scenario assuming an 80 year rotation of harvesting, and a Baseline Low (BASE2) scenario with an extended 120 year rotation. Finally, two thinning scenarios were created with varying thinning intensities (THIN HIGH and THIN LOW; see Table 6). All thinning treatments were applied at year 50 and assumed as a "thin from below" treatment, whereby stems were removed from the smaller size classes (specified in FORECAST to be applied evenly across four (of ten) smallest size classes). After 120 years, all thinning scenarios were clearcut harvested. Total simulation length was set to 240 years to encompass at least two full rotations of each scenario.

TABLE 6: MODELING SCENARIOS

Scenario	Planting		Ingrowth		Thinning Treatment	Harvest Rotation
CONTROL	Douglas-fir/Coastal western red cedar[2]	1200 stems/ha	Western hemlock	300 stems @ year 0	-	-
BASE1	Douglas-fir/Coastal western red cedar	1200 stems/ha	Western hemlock	300 stems @ year 0; 300 @ harvest	-	80 years
BASE2	Douglas-fir/Coastal western red cedar	1200 stems/ha	Western hemlock	300 stems @ year 0; 300 stems @ harvest	-	120 years
THIN HIGH	Douglas-fir/Coastal western red cedar	1200 stems/ha	Western hemlock	300 stems @ year 0 and after harvest; 100 @ thin	40% of stems removed @ Year 50	120 years
THIN LOW	Douglas-fir/Coastal western red cedar	1200 stems/ha	Western hemlock	300 stems @ year 0 and after harvest; 100 @ thin	25% of stems removed @ Year 50	120 years

4.2.4 Model calibration, assumptions and sensitivity analyses

For this study, growth and yield data used to calibrate FORECAST was taken from British Columbia Ministry of Forests stand tables and incorporated into a series of allometric equations in order to estimate total above- and below-ground biomass for various biomass pools (i.e. stembark, branches, foliage, roots, fruit, etc.). Planting and regeneration assumptions were developed from BC stocking standards and regional stand type information (BC Ministry of Forests and Range 2013; Smart 2010). Planting was assumed to occur the year following harvests with no regeneration delay. A lesser component of western hemlock was also assumed to establish (ingrowth; see Table 6) from natural regeneration following both harvest and thinning treatments.

At the time of all harvest treatments (thinning and clearcuts), 90% of harvested stemwood was assumed to be removed, with the remaining 10% being added to various litter pools. Similarly, 90% of stembark, 30% of branches and 30% of foliage were also assumed removed, with the balance remaining on site. Merchantable volume was calculated within the model assuming a 12.5 cm top diameter and 5 m log length.

[2] Planting was assumed to be 70% Douglas-fir and 30% western red cedar; based on personal communication with Brian Smart RPF (September 2013)

The merchantability estimate also includes a reduction for a 30 cm stump height. Harvested volume was assumed to be the total change in merchantable volume in years of harvesting, with the 90% removal of stemwood assumed to account for wastage and breakage.

Modeling in this study assumed the following over the length of the modeling period: 1) climate remained constant; 2) no natural disturbances occur; 3) soil carbon stocks remain constant. Large scale, stand-replacing disturbances are relatively infrequent for the project area considered; however an endemic level of disturbance is inevitable. Small scale disturbances from disease, insects and wind-throw would likely lead to additional recruitment of standing and lying dead wood, impacting the distribution and total carbon stocks within the stand. However, these disturbances were excluded in order to better isolate the effects of the harvest treatments by removing the additional influences that may occur, as has been used in other similar modeling studies (Harmon and Marks 2002; Eriksson et al. 2007; Seidl et al. 2007).

4.2.4.1 Sensitivity analyses

Further analysis was conducted on a number of the modeling inputs and assumptions in order to determine overall sensitivity of the modeled results. All modeling assumptions are listed in Appendix B. A list of the tested items as well as the results of the respective sensitivities are listed in Appendix C (FORECAST) and Appendix D (HSI).

5 RESULTS AND DISCUSSION

5.1 Results

5.1.1 Carbon stocks

The modeling results for total carbon storage over time, including all ecosystem carbon pools, as well as wood products, are shown in Figure 1. Displayed scenarios include the CONTROL, 80-year rotation clearcutting (BASE1), 120-year “extended-rotation” clearcutting (BASE2) and two 120-year rotation clearcutting with thinning variable intensity treatments (THIN LOW/THIN HIGH).

Results show that total stored carbon varies significantly between the scenarios. Figure 1 shows that over the entire simulation period, the CONTROL scenario stores significantly more carbon than any of the harvesting scenarios. Of the scenarios that included harvesting (here-in referred to as “managed scenarios”), higher carbon stocks were seen with extended rotation harvesting scenarios. Reductions in total carbon stocks following harvest treatments (shown in Figure 1) were mitigated by the transfer of carbon from live biomass to harvested wood products and litter. Also, the significant spikes followed by slow decline in total carbon stocks after harvests were caused by transfers of biomass carbon into the litter pool, followed by slow decomposition.

The addition of thinning treatments to the extended rotation scenario caused a slight decline in stored carbon immediately after thinning, but has little impact on long-term stored carbon. As well, higher intensity thinning treatments (THIN HIGH) caused a larger initial decline in stored carbon after thinning than lower intensity treatments (THIN LOW), but resulted in similar stored carbon over time.

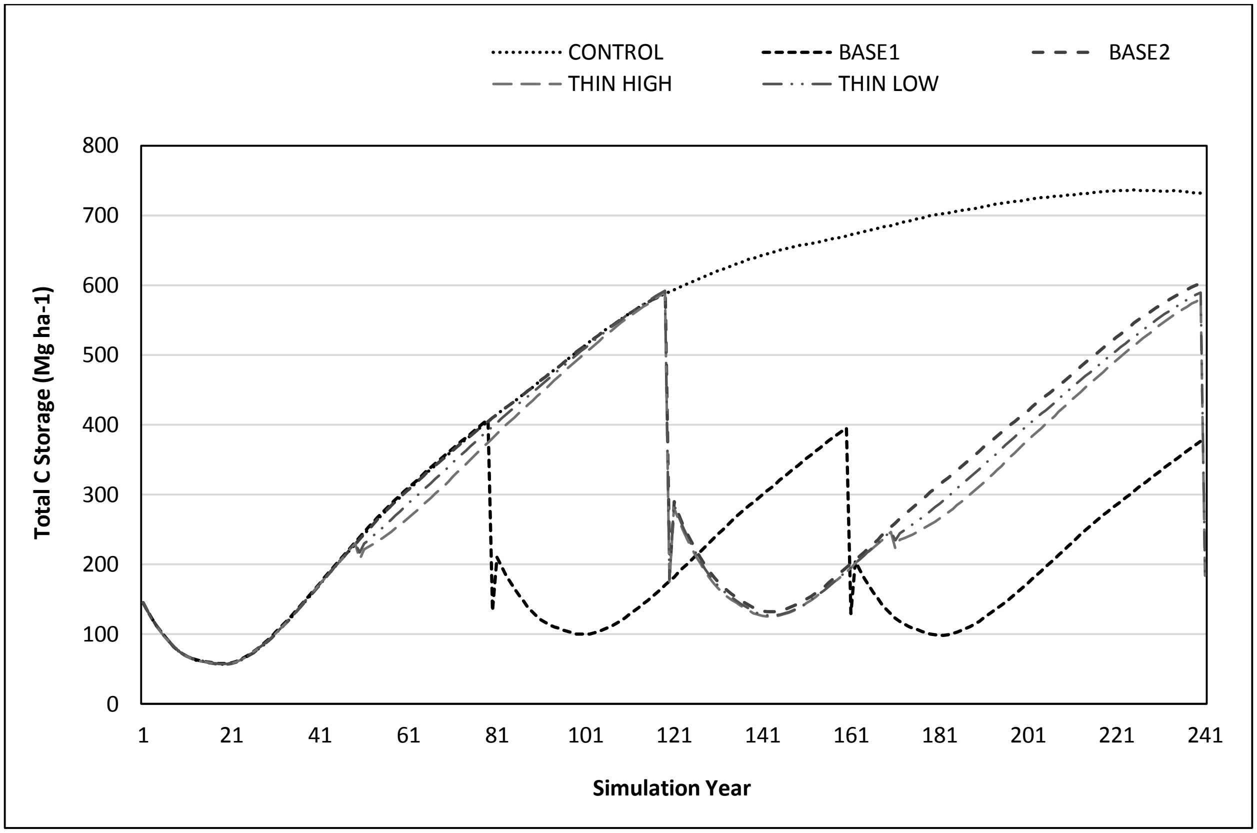


FIGURE 2: ECOSYSTEM CARBON STOCKS INCLUDING WOOD PRODUCTS BY SCENARIO

Figure 2 shows average carbon stocks over two time periods: the entire simulation period and a single management rotation (80 years for BASE1; 120 years for all other scenarios). Over the full 240 years, the CONTROL scenario showed the largest average carbon stock by a significant margin. This is intuitive as all other scenarios involved removal of biomass through harvesting treatments at various points throughout the simulation, while the CONTROL scenario did not. Also, scenarios involving extended periods between clearcut harvests showed significantly higher average carbon stocks than with a shorter rotation. The addition of thinning treatments to the extended rotation scenario caused a slight decline in average stored carbon, and little difference was seen between two thinning intensities.

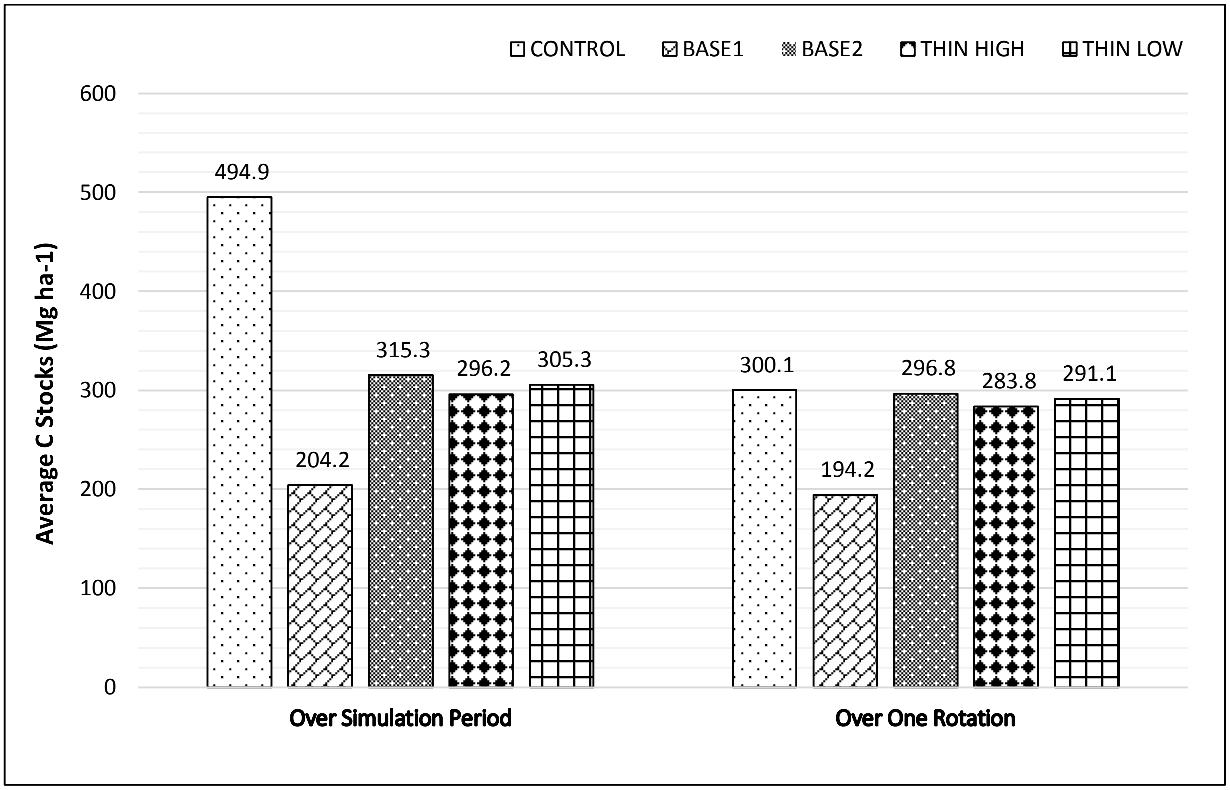


FIGURE 3: AVERAGE ECOSYSTEM CARBON BY SCENARIO

In addition to average carbon stocks over the entire modeling period, results are presented in Figure 2 as the mean carbon storage over a single management rotation. This method has been used in other carbon studies (Harmon and Marks 2002) in order to create a time independent comparison between scenarios. By averaging carbon values over a rotation, carbon stores are presented in a theoretical landscape with uniform age class (Harmon and Marks 2002; Harmon et al 1990; Krankina and Harmon 1994; Harmon 2001). Many of the results observed in the full simulation period averages were consistently seen in the single rotation averages. However, it is worth noting that over a single 120 year rotation, the lower intensity thinning scenarios resulted in only slightly lower average carbon stocks than the CONTROL.

In addition to the two thinning scenarios described above, a sensitivity analysis was conducted to determine if the timing of thinning treatments resulted in impacts on total carbon storage and annual carbon increment. Figure 3 shows average carbon storage resulting from variable years of treatment in comparison with the

CONTROL and baseline scenarios. Results show that variation of harvest treatments from year 40, 50 and 60 did not have significant impacts on total average carbon storage.

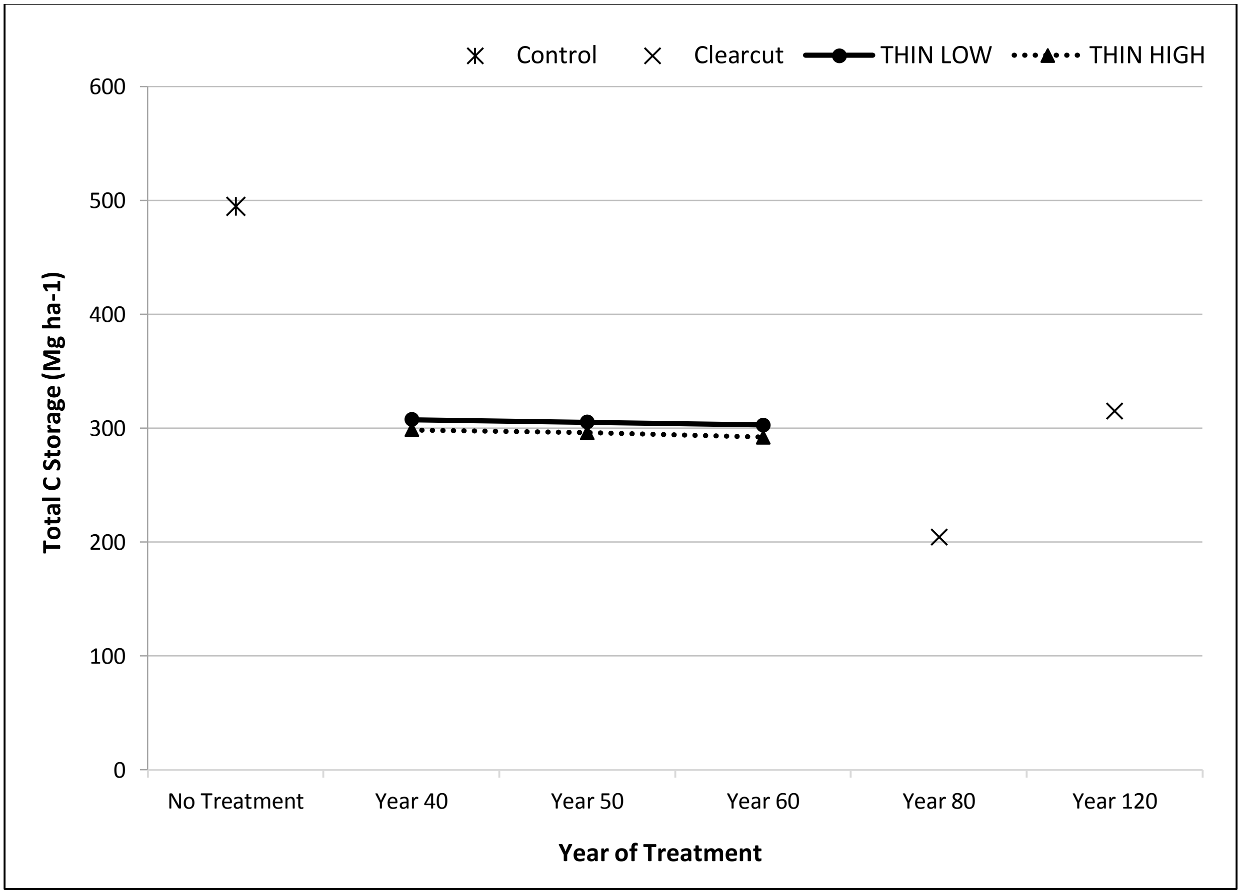


FIGURE 4: RESULTS OF SENSITIVITY ANALYSIS: AVERAGE CARBON STORAGE BY SCENARIO.

5.1.2 Northern goshawk habitat value

Figure 4 shows the HSI ratings for Northern Goshawk for each modeling scenario over the 240 year simulation period. When compared at the end of the simulation, the highest HSI rating are seen in the CONTROL scenario (~0.88; Good Class), and lowest ratings in the BASE1 (~0.35; Moderate Class). Both thinning scenarios resulted in similar final HSI ratings (~0.80; Good Class). Of all the managed scenarios, only the thinning scenarios resulted in “Good” habitat class rating (>0.75) at any point during the simulation. THIN HIGH reached “Good” habitat rating around year 100, while THIN LOW did so around year 110. The CONTROL scenario also reached the “Good” rating. However, it took significantly longer than the thinning scenarios, reaching it around year 137. Similarly, both thinning scenarios reached "Moderate" habitat class rating (>0.5) nearly 10 years sooner than the CONTROL scenario.

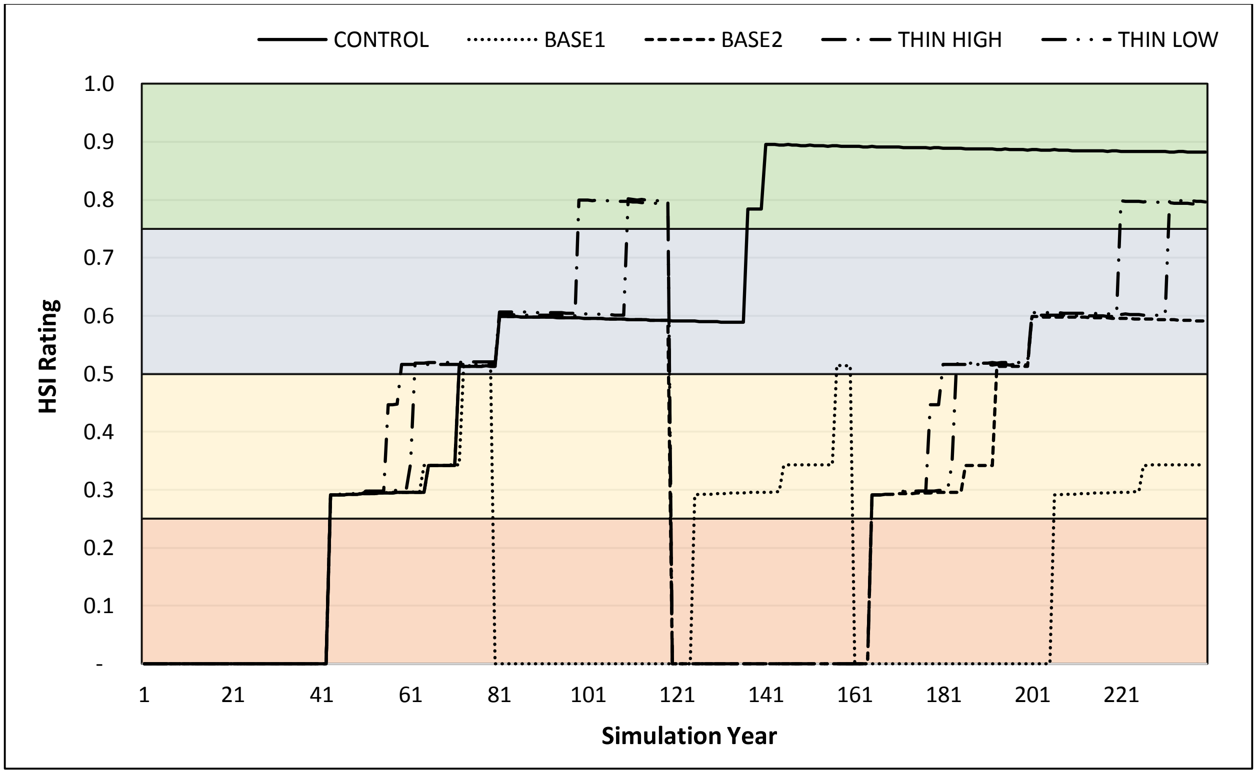


FIGURE 5: GOSHAWK HABITAT RATING OVER SIMULATION PERIOD BY SCENARIO

Figure 5 shows the average HSI ratings calculated over the entire simulation period, as well as one rotation period. The highest average rating over the entire simulation period was seen in the CONTROL scenario (0.58; Moderate Class), and the lowest average was in shorter rotation clearcutting (BASE1) scenario (0.15; Nil Class). While the maximum HSI rating for BASE1 did reach 0.51, the repeated harvest treatments and subsequent post-harvest periods of low habitat rating result in the low average. Extended rotation periods between harvesting (BASE2) resulted in significantly higher average HSI ratings. Also, the use of thinning treatments increased habitat rating compared to unthinned stands, with the higher intensity thinning treatments producing the highest average rating among the managed scenarios. Higher intensity thinning also produced greater average HSI ratings than lower intensity thinning.

Figure 5 also shows that over a single rotation period, the highest average goshawk HSI ratings were observed in the higher intensity thinning scenario, surpassing even the CONTROL scenario. Additionally, all thinning scenarios resulted in higher average HSI ratings over one rotation than either baselines or the CONTROL scenario. This appeared to be caused by an increase in average stand diameter within the thinning scenarios compared to the unmanaged (see Figure 6).

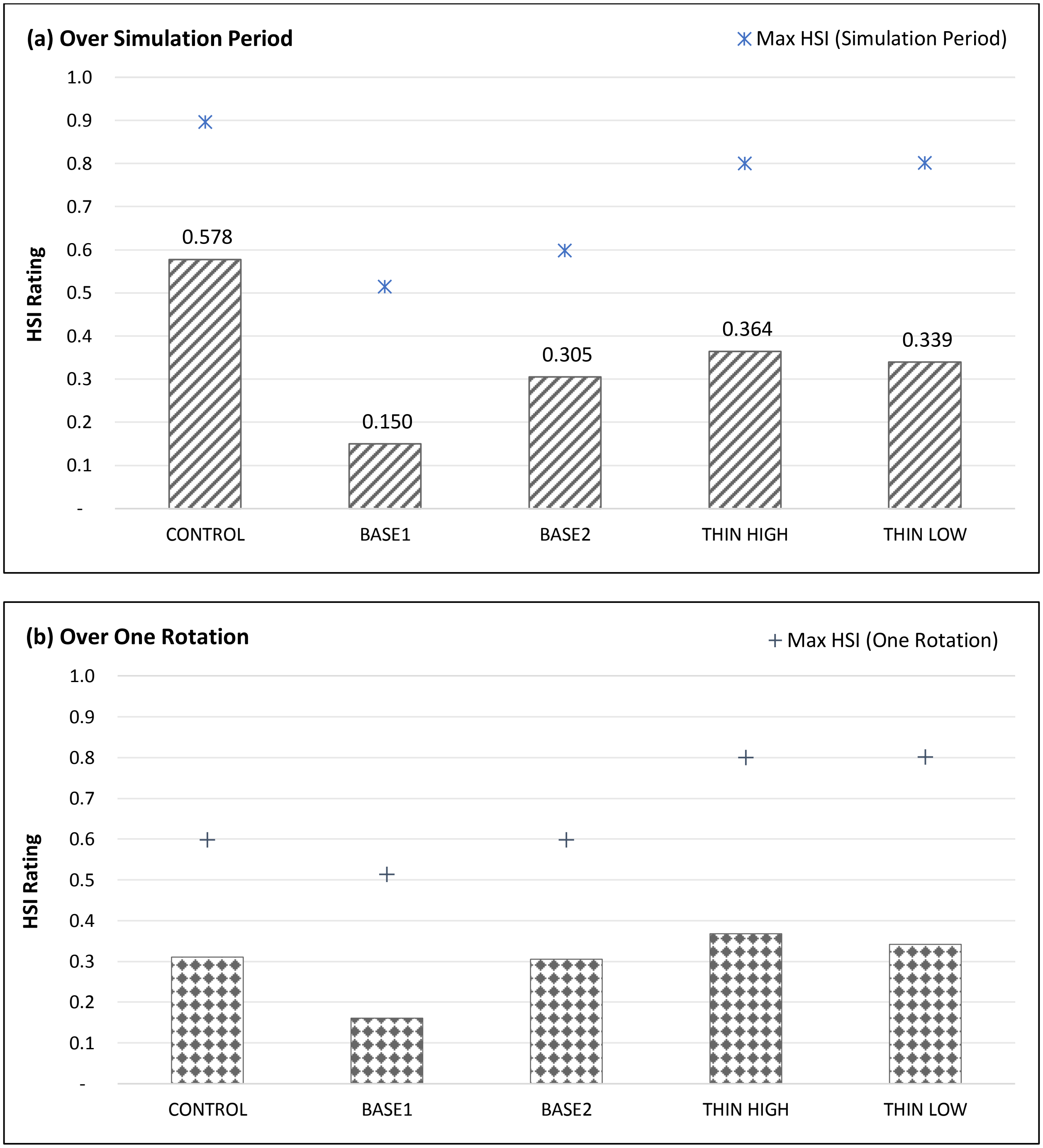


FIGURE 6: AVERAGE AND MAXIMUM HSI RATINGS BY SCENARIO: (A) OVER SIMULATION PERIOD (B) OVER ONE ROTATION

Figure 6 is a summary of average HSI rating by component habitat variables for each scenario. Average ratings were calculated for each variable over the entire simulation period, as well as a single rotation period. Figure 6 (a) shows that the CONTROL scenario showed the highest average component ratings for all included habitat variables, while the BASE1 scenario showed the lowest. This coincides with the total average HSI ratings shown in Figure 5. Average rating for species percentage remained consistent across all scenarios (0.89-0.90 ratings). This is because the initial stocking of all the scenarios was the same, and the overall species composition remained similar throughout the simulations. Average ratings for canopy closure, height, and age were similar across the thinned scenarios and the extended rotation scenario. Average diameter rating was the variable most affected by the thinning treatments with increases in diameter ratings over both considered time periods. Average diameter ratings were higher in all thinned scenarios than either BASE1 or BASE2.

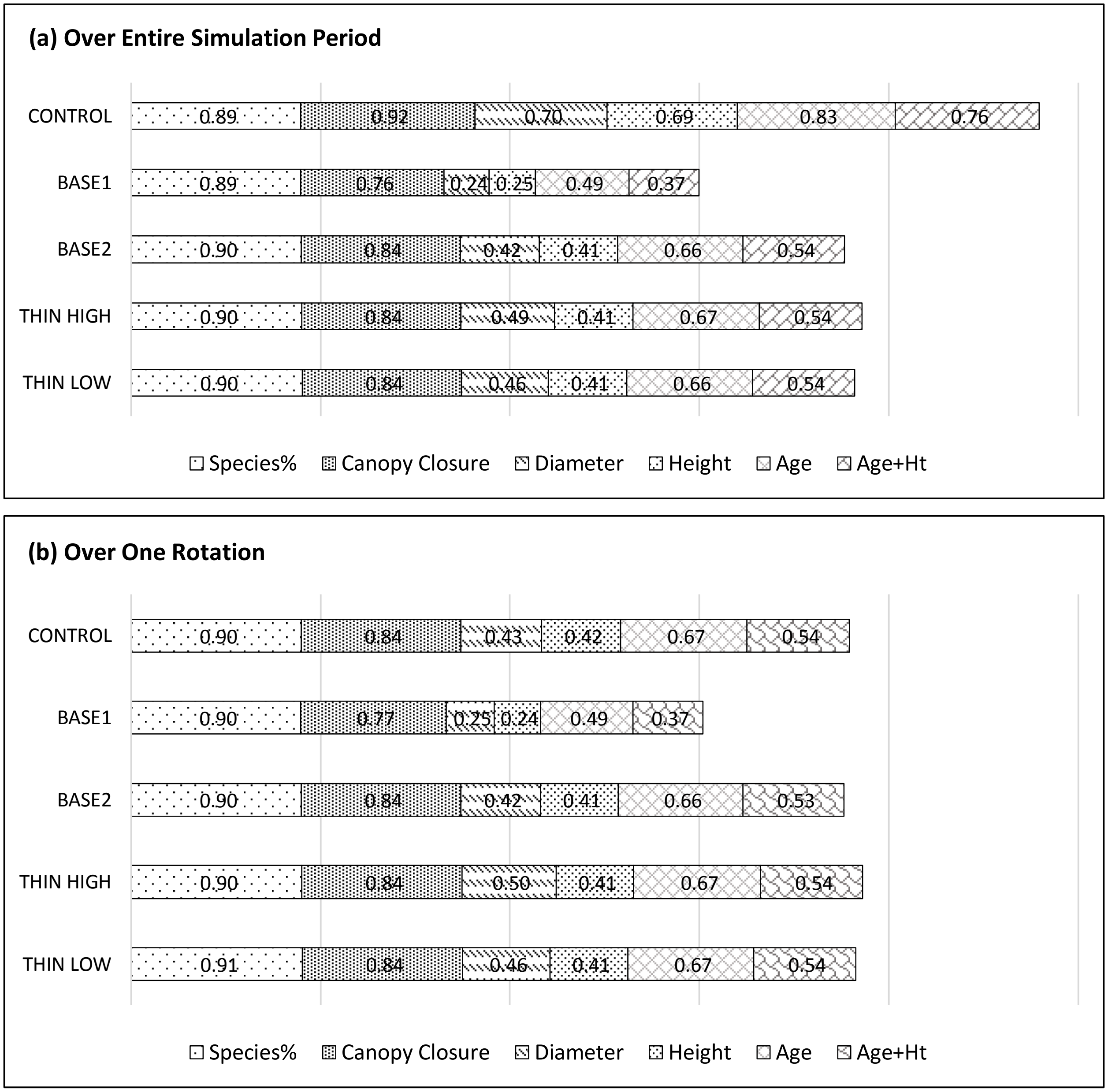


FIGURE 7: AVERAGE HSI COMPONENT RATINGS: (A) OVER ENTIRE SIMULATION PERIOD (B) OVER ONE ROTATION PERIOD[3]

5.1.3 Timber production

Figure 7 displays total harvested volume by scenario over the 240 year simulation period, as well as over one rotation period. 240 years encompasses two full rotations of the thinning scenarios and extended

[3] Values out of possible 1.0; Total HSI class rating = product of all component ratings)

rotation scenario, and three rotations of the shorter rotation scenario. The CONTROL scenario was a no-management scenario, and therefore had no harvested volume.

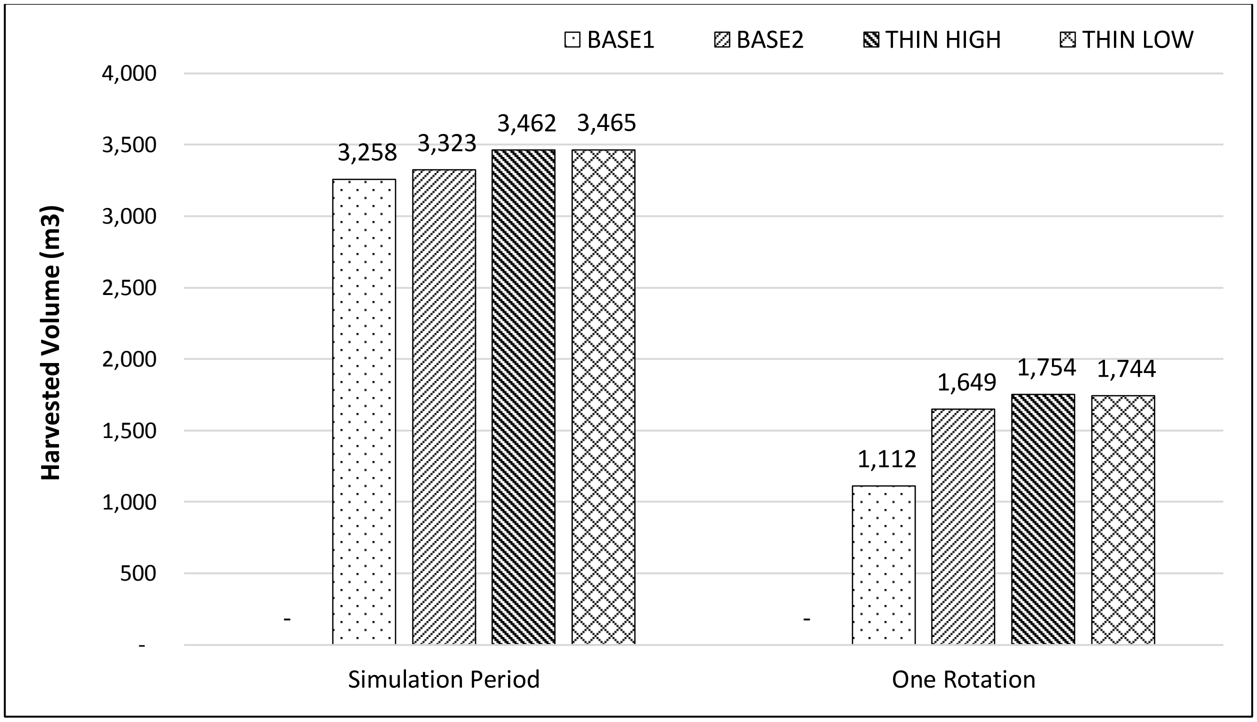


FIGURE 8: TOTAL HARVESTED VOLUME OVER 240 YEAR SIMULATION PERIOD AND A SINGLE ROTATION

Over both considered time periods, the greatest harvested volumes were seen in the thinning scenarios, slightly surpassing both BASE1 and BASE2 scenarios. BASE1 produced almost as much volume as BASE2, but over three rotations rather than two. Variation of thinning intensity between THIN HIGH and THIN LOW produced no significant difference in total harvested volume.

Figure 8 summarizes the results of the sensitivity analysis around year of thinning treatment and thinning intensity. When comparing the thinning scenarios, variance of both percent stems removed (HIGH to LOW) and timing of thinning had little effect on total harvested volume. All thinning scenarios resulted in a slightly higher harvested volume than either clearcut scenario. Additionally, longer rotations between clearcuts resulted in slightly higher amounts of harvested volume over the entire simulation period.

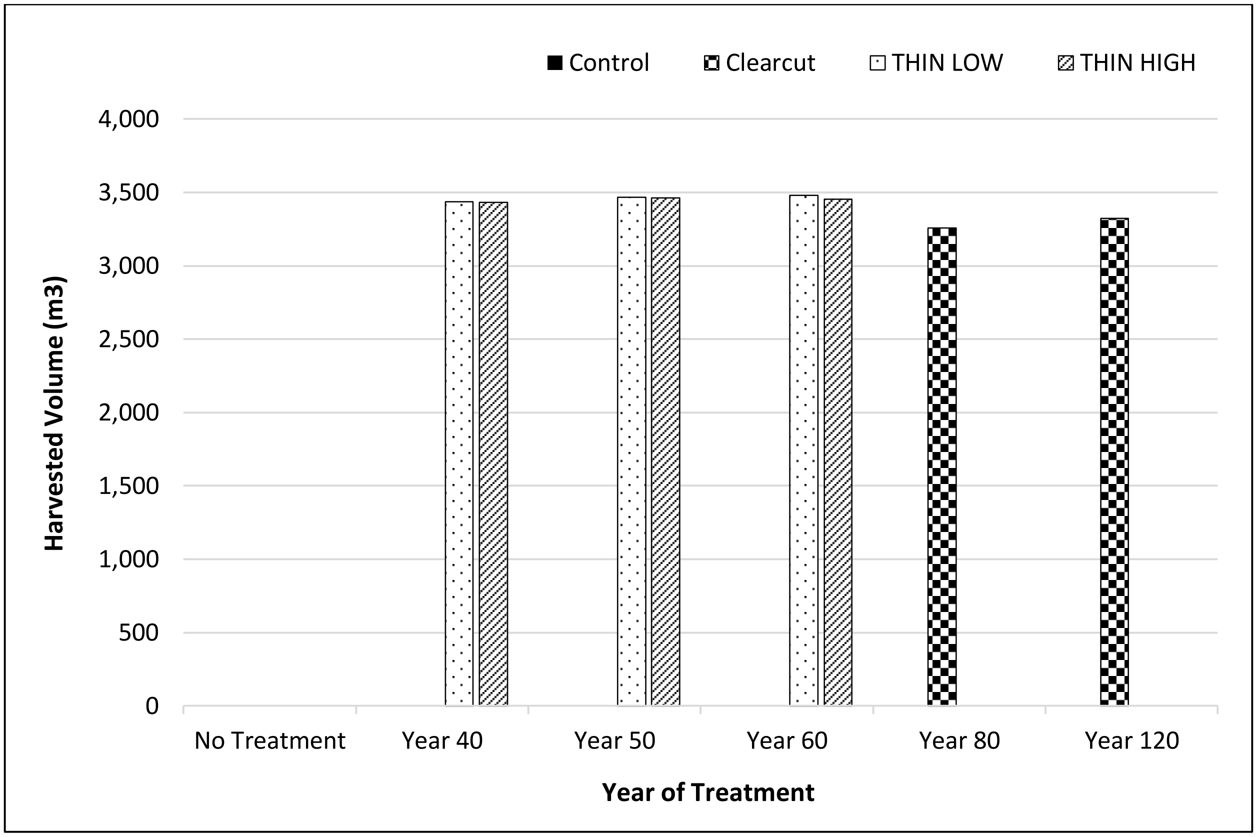


FIGURE 9: TOTAL HARVESTED VOLUME OVER SIMULATION PERIOD BY TREATMENT TYPE (CLEARCUT OR THIN + CLEARCUT) AND TREATMENT YEAR

5.2 Discussion

The results suggest that if management objectives were simply to maximize carbon stocks, leaving a stand in an unmanaged, conservation condition is the best option. This result is supported by research demonstrating that in forests where stand-replacing natural disturbances are infrequent (such as PNW coniferous forests), highest levels of carbon stocks can be achieved by leaving mature stands in an unmanaged condition (Harmon et al. 1990; Kurz et al. 1998; Smithwick et al. 2002). Over the 240 year simulation period, the unmanaged stand also produced the highest average ratings of goshawk habitat, suggesting conservation also provides high habitat value.

However, full forest conservation is not always suitable for areas with multiple resource demands. If a level of timber production is also desired, high amounts of carbon stocks are generated through an extension of rotation period between clearcut harvesting (Harmon et al. 2009; Smithwick et al. 2007; Harmon and Mark

2002). Results show that the extension of harvest rotation period, subsequent increase in stand age, and storage of carbon within wood products, have a much larger impact on long term carbon stocks than any applied thinning scenario. This supports a strongly documented relationship between stand age and carbon storage (Law et al. 2003; Harmon 1990; Smithwick et al. 2007). Extended rotation also produced greater harvest volume over 240 years than the shorter rotation periods.

The relatively small difference in carbon stocks between the thinned and unthinned scenarios suggests light thinning treatments have slight negative impacts on long term carbon stocks. This is consistent with a number of other thinning studies in western North America (Finkral and Evans 2008; Campbell et al. 2009). Thinning treatments with higher biomass removal and later treatment ages also resulted in lower total stocks throughout the simulation period. This suggests that in the simulations, the increase in individual stem-level productivity following thinning (Roberts 2008) did not fully compensate for the stand-level loss of total biomass from the treatment within the 120 year rotation periods (Clark et al 2011; Campbell et al. 2009). Studies have indicated that thinning treatments and their associate redistribution of growth potential allow stands to continue higher levels of productivity into older age classes than untreated stands (Oliver and Larson 1996). Given the relatively small difference in carbon stocks between these scenarios, it is possible that if these thinned stands were left to grow beyond 120 years, total carbon stocks would surpass the unthinned totals in time. While this has not been fully studied in PNW coniferous forests, it has been observed in the Appalachian hardwood (Hoover and Stout 2007) and Australian bottomland forests (Horner et al. 2010).

The highest average ratings of goshawk habitat over the simulation period were observed in the CONTROL scenario, suggesting that if maximum priority was placed on goshawk habitat value, a conservation/unmanaged approach would yield the best results over the long term. Comparison of the managed scenarios, however, indicates extended rotation periods and thinning treatments can cause higher habitat value due to increased average tree diameters. Increase in average DBH is consistent with other studies of PNW coniferous forests that have shown increases in average stand diameter after thinning treatments (Oliver and Larson 1996; Davis 2007; Sprugel 2009; Dodson et al. 2012) in PNW coniferous forests. Impacts of thinning on stand diameter are dependent on the intensity of the treatment, with a sufficient number of stems needing to be removed to create large enough canopy gaps between residual trees to promote additional DBH growth (Oliver and Larson 1996; Davis 2007). Use of thinning treatments of various intensities could be incorporated with existing heterogeneity in stand structure (i.e. gap opens, etc.) to further promote DBH growth (Dodson et al. 2012) and habitat value.

Study results also show that thinning affects the time after harvest needed to achieve higher HSI ratings and provide high quality habitat. While the CONTROL scenario had the highest average rating over the simulation period, it took nearly 135 years to reach the "GOOD" class rating (>0.75). Similar ratings were achieved in the thinning scenarios 25 to 35 years sooner. Also, thinning treatments were able to produce "MODERATE" class habitat (>0.50) 10 years sooner than the CONTROL scenario. This acceleration of habitat value was again caused by increased average DBH sizes within the thinned stands. This could potentially allow managers to promote quality goshawk habitat within second growth stands at earlier ages than would occur naturally.

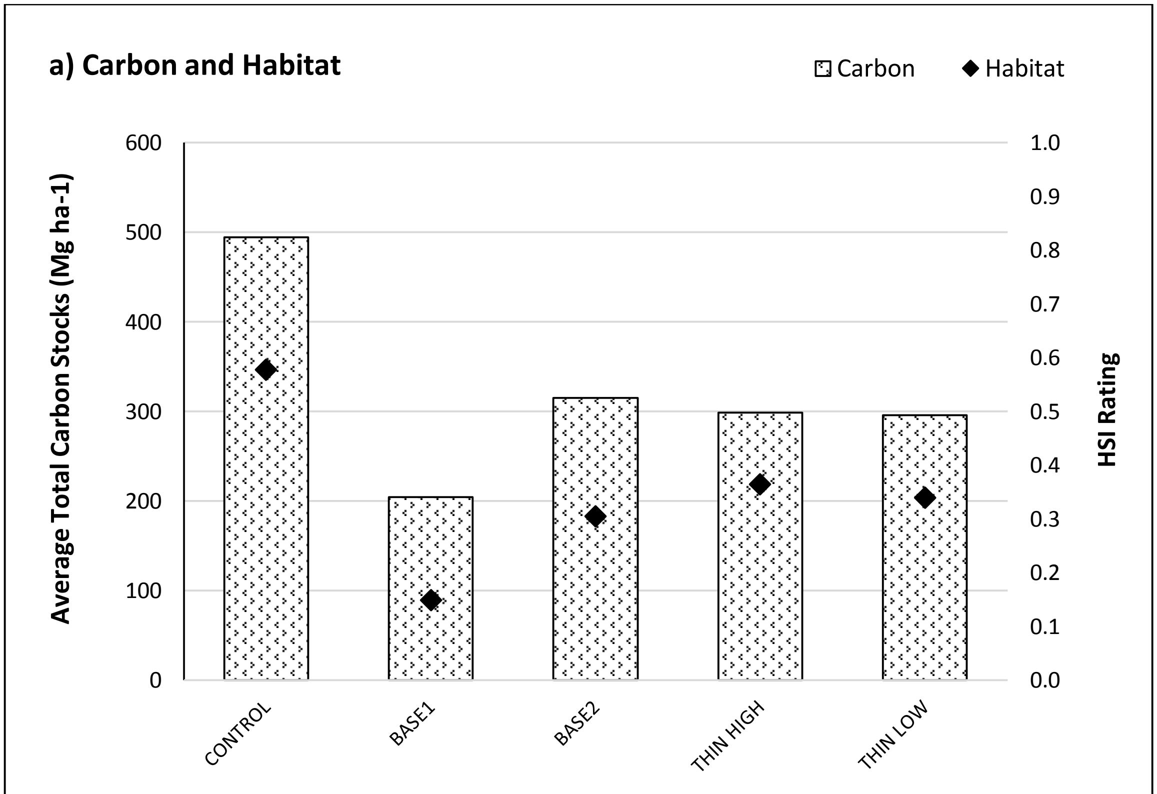
Average HSI ratings in the thinning scenarios were also significantly reduced by the clearcut harvests after the 120 year rotation periods. If thinned stands were left unharvested beyond 120 years, they would produce higher average ratings that would likely surpass the CONTROL in time. Further analysis of harvest rotation age would be needed to determine this crossover point.

Thinning treatments showed slight positive impacts on total harvested volume when compared with untreated stands. It should be considered, however, that the harvest log size distribution between the treated and untreated scenarios is likely different. Thinning treatments were of the "thin from below" type, harvesting from smaller sizes classes, and thus producing smaller logs (minimum stem diameter of thinned stems at year 50 was around 10 cm). Conversely, thinning treatments caused an increase in average stem diameter compared to untreated stands (nearly 10 cm increase from BASE1 after higher intensity thin), resulting in larger log sizes at the 120 years rotational harvests. Detailed log size distribution data was not available within the models used, so further analysis would be necessary to quantify this potential increase in log value.

5.2.1 Complementary benefits between values

The results demonstrate that while it is apparent that when considering multiple management objectives, no single stand-level management strategy optimizes all values, there are management strategies that promote potential complementary benefits. This is demonstrated in Figure 9, which displays the co-benefits and trade-offs for combinations of values resulting from each scenario: a) average carbon stocks and average HSI value b) timber harvested and average HSI value and c) average carbon stocks and timber harvested.

As shown in Figure 9a, if timber production is not a desired value, the highest potential complementary benefits between carbon sequestration and goshawk habitat are produced through a conservation approach. However, of the timber producing scenarios, significant gains in both carbon stocks and habitat value can be achieved with little impacts on total timber production through the extension of rotation age between harvests. Beyond that, modest gains in habitat value and timber production can be generated with minor losses to carbon stock by use of low intensity thinning treatments. These results may be applicable in the context of an extended rotation age carbon sequestration project, in which land managers wish to increase goshawk habitat value in addition to carbon sequestration. Significant gains in long terms carbon stocks would be generated through extended harvest rotations, while thinning treatments could increase long-term habitat value with minimal impact on stored carbon.



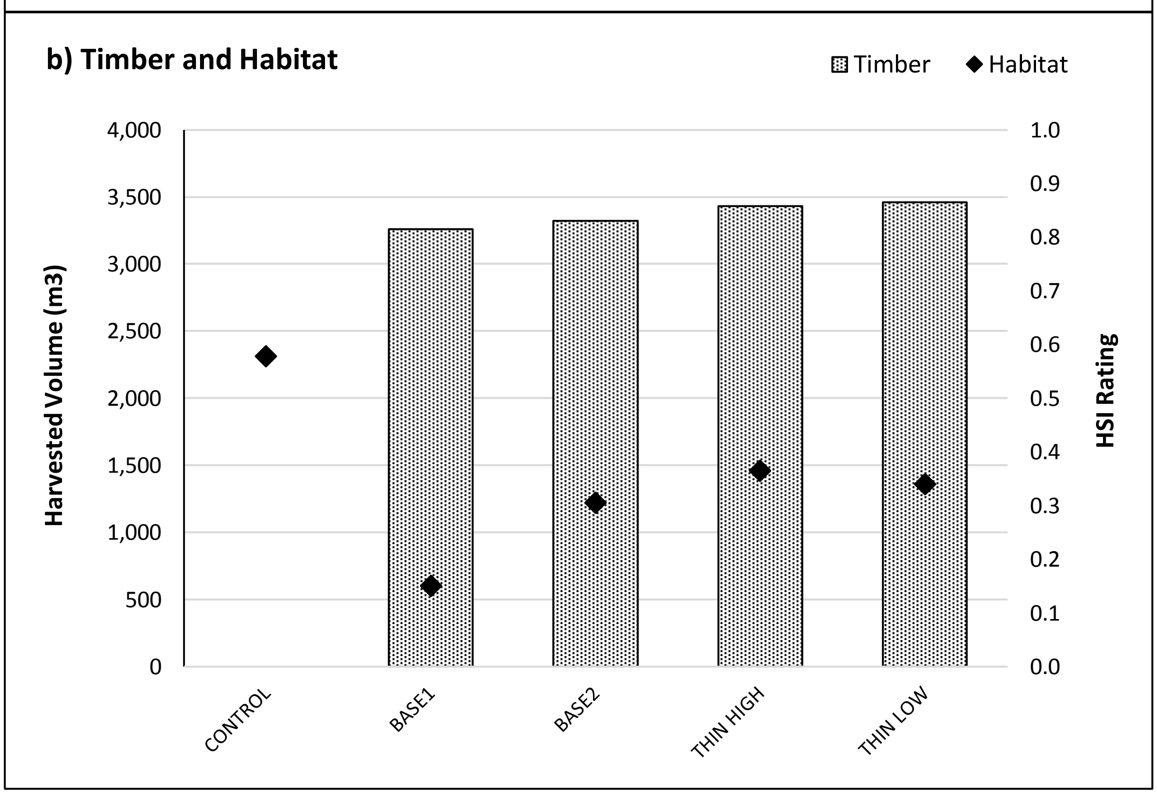


Figure 10: Trade Off Comparison Between Values: (a) Carbon Storage and Goshawk Habitat (b) Timber and Goshawk Habitat and (c) Carbon and Timber by Scenario

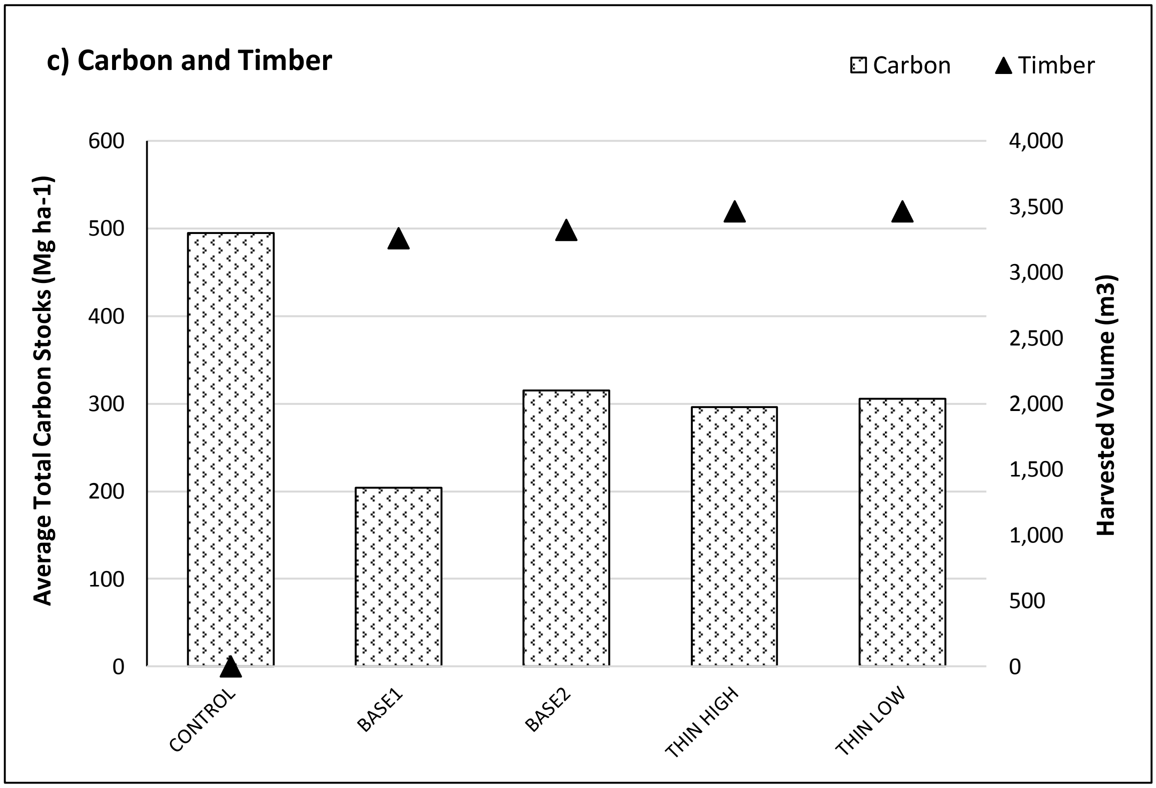


FIGURE 10: TRADE OFF COMPARISON BETWEEN VALUES: (A) CARBON STORAGE AND GOSHAWK HABITAT (B) TIMBER AND GOSHAWK HABITAT AND (C) CARBON AND TIMBER BY SCENARIO

There is a clear long-term conflict between timber harvesting and goshawk habitat caused by the rotational clearcut treatments, which effectively render all habitat values achieved through a rotation period temporary when applied at the stand level. However, when considering impacts over a single rotation, goshawk habitat rating in both thinning scenarios immediately before final harvest far surpassed the unthinned stands, as well as the CONTROL. As such, if a combination of these management strategies were applied at a landscape level, areas of high habitat value could be dynamically maintained over time. Required nesting areas of goshawks are relatively small (12-50 ha) (Mahon 2009), and regional studies in Washington (Mahon and Doyle 2005) and Northern Idaho (Moser and Garton 2009) have found that goshawk nest reoccupancy is largely unaffected by nearby harvesting, provided an adequate amount of potential nesting area was kept unharvested (Saga and Selas 2012). Goshawks have also been shown to exhibit strong fidelity to nesting areas, with old nests sometimes being reused by new birds and continued use of nests even after failed breeding attempts (Mahon 2009). This could allow managers to use extended rotation ages and thinning treatments to promote further nesting area over a landscape, while maintaining a level of timber harvesting.

This same approach could be applied for carbon and timber management, prioritizing particular areas for specific values based on the existing stand or site type and applying appropriate management strategies to best promote those values (Marland and Marland 1992). Areas of high carbon stocks or poor growth rates could be put into conservation to preserve existing carbon storage and habitat value. Extended rotation harvesting could be applied in more productive areas, allowing continued production of timber products, along with additional carbon sequestration compared to a shorter rotational harvest. Revenue from timber could then help to fund less economically viable thinning treatments for the habitat benefit in moderately productive areas.

5.2.2 Additional Limitations

Habitat results of this study are based on the assumption that production of high quality habitat will result in greater occupancy by goshawks. While it is intuitive that species would utilize higher quality habitat, this “if you build it they will come” (Ahlering and Faaborg 2006) assumption can over-simplify the problem. As such, the use of HSI’s to identify or create “high quality” habitat does not always ensure presence or abundance of a particular species. Other factors independent of habitat variable such as climate, disease, predation, history, and human impact can have significant impacts on species distribution (Schamberger and O’Neil 1986). Also, the results of HSI models must be applied with careful consideration. Results of this study indicated that the primary change in HSI ratings between the observed scenarios was an increase with average stand diameter, with all other habitat variables remaining consistent.

While large diameter trees have been associated with high quality goshawk habitat, consideration must be given for other factors that can affect goshawk nesting.

Additionally, this study focuses specifically on Northern Goshawk habitat with a coastal coniferous forest type. While increasing heterogeneity in stand structure can provide habitat for a wider range of species than homogenous stands (Dodson et al. 2012), regional studies have also shown that populations of different bird species can respond both positively and negatively to thinning treatments (Chambers et al. 1999; Cahall 2013). Given that different species of birds (and other vertebrates) have natural adapted to a wide range of stand structural conditions, it is not appropriate to apply the same strategies everywhere (Bunnell and Huggard 1999). Consideration of potential impacts on other species would be required before any management practices were applied.

Additional sensitivity analyses were conducted on a number of key assumptions made with both the ecosystem and habitat models. The results are shown in Table 9 and Table 10 of the Appendix. While a few assumptions demonstrated moderate sensitivity to overall carbon and HSI values per scenario, the relative results between scenarios did not change.

6 CONCLUSIONS AND FURTHER RESEARCH

6.1 Conclusions

The results of this modeling study predict that forest management prescriptions can have both positive and negative impacts on carbon storage, Northern Goshawk habitat and timber production. While no single management strategy provides maximum benefits from all three values, use of extended rotation periods between harvesting and low intensity thinning treatments can result in complementary benefits for multiple values. In addition, these results show that thinning treatments can reduce the time required to develop high quality habitat over that of either unmanaged or clearcut management. If selectively applied over a landscape scale, these management prescriptions help to provide a range of forest values and address a variety of resource demands.

In addition, the modeling framework developed in this study provides a means of quantifying benefits and trade-offs from carbon, wildlife habitat and timber values. This same approach could be applied to other project areas and wildlife species in order to explore specific management questions.

6.2 Further Research

Recent studies have also emphasized the impacts of habitat fragmentation on bird populations, suggesting that not only is local habitat structure important, but also regional habitat distribution (Ahlering and Faaborg 2006). While regional studies have concluded that thinning treatments were an effective way to maintain and promote bird habitat in PNW coniferous forests, they also suggest a better approach may be to incorporate thinning along with conservation at the landscape level (Cahall 2013). Managing for carbon at landscape level requires averaging sequestration rates of individual stands, as some areas may be increasing in C stocks, while others are decreasing post-disturbance (Harmon 2001). A balanced disturbance regime may be the best approach to increasing this average (Harmon 2001). Care should also be taken when inferring stand-level results at a wider scale because of potential interaction and feedback between spatial scales (Bugmann et al. 2000) both in terms of carbon and habitat. Further study incorporating the results of our stand-level study at a landscape level could be informative in this regard.

The modeling approach developed in this study could assist in this regard and be adapted to incorporate other species HSI's. Harmon 2001 described the issues of scale in carbon stock management by saying that while a single tree only provides temporary carbon storage before dying, a properly balanced forest can ensure continued carbon through transfers between carbon pools and continued growth (Harmon 2001). A similar approach can be applied to habitat management as well. Further landscape level analysis should be conducted in order to find the best management practices to provide a range of structural conditions at a number of spatial and temporal scales (Bunnell and Huggard 1999; Bunnel and Dunsworth 2009).

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APPENDICES

Appendix A - Habitat Variables Included in Other BC Northern Goshawk Studies

Mahon et al. 2003 / Rumsey et al. 2004	Manning et al. 2002 / Marquis et al. 2005	Keystone Wildlife Research Ltd. (2008)
Tree Height	Stand Age	Stand Height/Stand Age
Canopy Closure	Site Index	Canopy Closure
Tree Species Composition	Region	Tree Species
Distance from Edge	Leading Species	Biogeoclimatic Zone
	Biogeoclimatic Zone	Elevation
	Crown Closure	

Appendix B - Table of Modeling Assumptions

Assumption	Value	Reference/Rationale
Wood Products Half-Life	20 years applied to entire harvested volume;	Conservative estimate based on values from Skog and Nicholson 2000
Soil carbon	*Excluded from quantification*	To isolate impacts of management scenario
Constant Climate	Growth rates remained constant over subsequent rotations; no change for climate impacts	Impacts of climate difficult to predict with the model; exclusion further isolates the impacts of each scenario; consistent with similar modeling studies
Western hemlock ingrowth	300 stems per ha after clearcut; 100 after thinning	Based on personal communication with Brian Smart RPF (September 2013)
Carbon Pool distribution at harvest; OAF	Stemwood/stembark = 90% removed; branches/foliage = 30% removed	Taken from Seely et al. 2002 and recommended through personal communication for project area with Brian Smart RPF (September 2013)
Merchantable volume calculations	Min top DBH = 12.5cm; stump height = 30cm; log length = 5m	Coastal BC standard values
Stocking standards	1,200 stems per ha; 70% Fd/30% Cw	Values based on *Reference Guide for FDP Stocking Standards* - updated 2013 and Smart 2010
Harvest priority between species for thinning	All three species given equal harvest priority	Simplify simulations to exclude market influences
HSI values for stand height and DBH were only calculated from the initial cohorts established at the beginning of each rotation, not including ingress regeneration after thinning treatments	The HSI formula used average stand height and DBH as a structural variable for calculating overall habitat rating. These averages were calculated from the total heights of all living stems at a given year.	Immediately following the thinning treatments, a small cohort of western hemlock is established as natural regeneration. When this cohort appears in the model, the average height and DBH of all living stems within the immediately decreased. To avoid this error, average DBH and stand height were calculated based on the initial cohorts established before thinning occurred.

Appendix C - Sensitivity Analysis Items, Tests and Conclusions: FORECAST

ITEM	DESCRIPTION	TEST	RESULTS	IMPACTS
Year of thinning treatments	All thinning treatments are applied at year 50	Vary thinning treatment year by +/- 10 years	See Results sections	
Product half-life	Simplified approach was taken applying a mid-range half-life to all harvested volume, knowing that a variety of products would actually be created.	Vary half-life +/- 25%	+/- 25% Half Life value results in +/- 3-5% HWP storage in all harvesting scenario tested. Impacts greatest in BASE1; least in BASE2	Insensitive

Appendix D - Sensitivity Analysis Items, Tests and Conclusions: Habitat Model

ITEM	DESCRIPTION	TEST	RESULTS	IMPACTS
Canopy closure variable ratings	Ratings from Keystone Wildlife Research Ltd. (2008) used as it was regionally developed from Toba Inlet	Substituted Mahon et al. 2003 values	Range of -6% (CONTROL) to -19% (BASE2) reduction in 240 year average CC rating; no change in ranking HSI ratings. High canopy closure in later years of all but Control bring score down. Thin scenarios never reach "GOOD" class rating.	Moderately sensitive
Height variable ratings	Ratings from Keystone Wildlife Research Ltd. (2008) used as it was regionally developed from Toba Inlet; used series of height classes	Substituted Mahon et al. 2003 values; linear rating	Range from 1-7% increase in Height rating. Largest increase seen in BASE1 due to higher ratings in lower height. <1% decrease in total rating for all but BASE1, which has a 2% decrease	Very insensitive
Age variable ratings	Ratings from Keystone Wildlife Research Ltd. (2008) used as it was regionally developed from Toba Inlet; used series of age classes	Substituted Mahon et al. 2003 values; linear rating	Decrease in all age ratings; largest impact on BASE1 scenario (-32%), least on Control (-6%). Lesser impact on overall rating (decrease in all). Does not change ranking of scenarios. THINS impacts less than BASE1/BASE2	Moderately sensitive
Canopy closure input value	Calculated using the minimum value between included species	Substitute average value between species	<1% change in average canopy closures for all tested scenarios.	Very insensitive