Adapting Forest Management to Climate Change in the Acadian Forest Region: A Strategic Modeling Approach

by

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Abstract

Climate change will impact forest dynamics in the Acadian forest region, necessitating adaptive strategies for sustainable forest management. This dissertation examines the impacts of climate change on forest dynamics and management using inventory data from the 5th Canadian Division Support Base Gagetown and climate projections from the IPCC Fifth Assessment Report (RCP4.5 and RCP8.5). Climate-sensitive tools were integrated into strategic forest planning across three interconnected studies.

The first chapter synthesizes projected climate scenarios and their implications for New Brunswick's forests, providing a reference for climate variables and their expected impacts. By 2071–2100, increases in temperature and growing degree days, along with reduced summer water balance, are expected to intensify disturbances such as fires and pest outbreaks. Boreal species like balsam fir and black spruce are projected to decline, while temperate deciduous species such as red maple and American beech are expected to expand. Adaptive silviculture strategies: assisted migration, thinning, and innovative harvest methods, are discussed to enhance forest resilience.

The second chapter presents a method for integrating climate-sensitive yield tables and transition rules into strategic planning using the PICUS stand model and the Woodstock landscape model. A rotation-age–based planning approach was used. Simulations under different climate scenarios show a shift toward warm-adapted species, declines in cold-adapted species, and reduced merchantable wood volume, posing

economic and wood supply risks. This underscores the need to integrate climate change into forest planning to avoid overharvest and ensure long-term resource availability.

The third study assesses climate change impacts on treatment scheduling, wood supply, economic returns, and harvesting practices. Climate-sensitive yield tables and transition rules were developed for two partial-cutting silvicultural interventions. Using linear programming in Woodstock, treatment schedules were optimized to maximize stumpage revenue under three climate scenarios. Clear-cutting remained dominant, but high- and low-retention harvesting increased under warming. A major shift from conifer to deciduous dominance occurred, yet partial cutting mitigated revenue losses. This highlights the value of a diverse, climate-adapted silvicultural toolbox to help buffer negative climate impacts on forest management.

Keywords: climate-sensitive optimization, dynamic transition rules, dynamic yield tables, species composition shift, strategic forest planning

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Chapter 1. Introduction

1.1 Climate change impacts on forests

Climate change poses unprecedented challenges to forest ecosystems worldwide, altering temperature and precipitation regimes, increasing the frequency and severity of natural disturbances, and accelerating changes in forest structure and function (Allen et al. 2010, 2015; Hartmann et al. 2022). The rate at which climate change impacts will unfold in the future remains uncertain, largely dependent on the pace of warming, which is typically defined by three scenarios from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change in 2014: optimistic (RCP2.6), moderate warming (RCP4.5), and severe warming (RCP8.5; Pachauri et al. 2015; Hausfather and Peters 2020). Projected impacts are particularly acute in transition zones such as the Acadian forest region, which bridges boreal and temperate ecosystems (Boulanger et al. 2017). As a result, species such as balsam fir (*Abies balsamea*), spruces (*Picea* sp.), and trembling aspen (*Populus tremuloides*) integral to the region's ecological and economic fabric, are showing signs of reduced growth, mortality, and limited regeneration due to climatic stressors (Taylor and MacLean 2011; Taylor et al. 2017; Andrews et al. 2022). Many boreal species are already at their southern distribution and tolerance limits within the Acadian forest. Increased stress from rising temperatures and changing moisture regimes make them even more vulnerable to the impacts of climate change (Vanderwel et al. 2013; Andrews et al. 2022).

These challenges are compounded by the fact that forest tree species are often unable to adapt quickly enough to match the pace of climate change, leading to shifts in species

composition, reduced biodiversity, and diminished forest resilience (Sittaro et al. 2017; Collier et al. 2023). Consequently, the sustainable flow of forest goods and services, including timber production, is increasingly at risk (Taylor et al. 2017; Baskent et al. 2020; Brecka et al. 2020).

Despite the growing awareness of the impacts of climate change on forest ecosystems, managers continue to struggle with incorporating its effects into their management and planning strategies (Hosen et al. 2020; Serra et al. 2022). One problem is the lack of comprehensive studies synthesizing the impacts of climate change in many regions, including for the Acadian forest, in ways that are applicable to strategic forest planning.

1.2 Forest management and planning under climate change

Traditional forest management strategies have long relied on static assumptions about climate conditions, a paradigm increasingly at odds with the accelerating pace of environmental change (Bettinger et al. 2016; Daniel et al. 2017; Taylor et al. 2017). These static assumptions fail to account for the variability and unpredictability introduced by climate change, including shifts in species composition, altered growth rates, and increased vulnerability to natural disturbances. To address these shortcomings, multiple approaches to integrating climate change into strategic forest planning have been explored in North America over the past decade.

Daniel et al. (2017) introduced a novel method by converting deterministic forest planning models into stochastic, spatially explicit state-and-transition simulation models. By incorporating Monte Carlo simulations, this approach assessed the impacts of

uncertainties, offering a risk-based framework for forest management. On the other hand, Ashraf et al. (2015) and Searls et al. (2021) developed growth modifiers applied to baseline yields, providing a relatively straightforward method to adjust forest growth projections based on specific stand-level climate modeling. These modifiers, while innovative, often lack the complexity needed to capture intricate interactions between species and environmental variables especially in regeneration and mortality. Other studies have focused on modifying treatment intensities and implementing stand-specific objectives to influence post-treatment regeneration, emphasizing the importance of tailored management approaches under changing climatic conditions (Nagel et al. 2017; Gustafson et al. 2020). Process-based models were used to calibrate transition rules by Taylor et al. (2020) effectively modeling regeneration patterns under a limited quantity of treatments under climate change revealing insights into how regeneration might vary across different landscape compositions and management regimes.

While these methods have introduced significant advancements in forest management, they often fall short in capturing the complete interactive and dynamic processes of forest systems under changing climates (Ashraf et al. 2015; Metsaranta et al. 2024). Many rely on static yield tables and expert-defined transition rules, which do not adequately account for tree-level interactions or the adaptability of species to shifting environmental conditions. This rigidity limits their applicability to the dynamic realities of climate change especially under long planning horizons. Additionally, most existing frameworks rely heavily on empirical data derived from historical conditions, making assumptions that may not hold under future climate scenarios which can lead to unpredicted species decline, wood supply shortages, and increased exposure to natural disturbances.

Another critical limitation lies in the complexity and accessibility of many proposed methods. While advanced modeling techniques such as stochastic simulations and process-based models provide valuable theoretical insights, they often require extensive expertise and computational resources that greatly deviate from current non-climate-adapted methods, creating barriers for practical implementation in real-world forest management contexts.

1.3 Objectives and hypothesis

This Ph.D. project investigates the complex impacts of climate change on forest management planning within the Acadian forest region, focusing on developing adaptive strategies through a constructivist approach across three interconnected research chapters. Using the forest inventory of the 5th Canadian Division Support Base – Gagetown, where the Government of Canada acts as both landowner and decision maker, combined with climate data and projections from the Ouranos Climate Center, this research explores and tests a novel approach that integrates yield tables and transition rules that are dynamic to climate change into strategic forest planning. This study also assesses the potential effects and risks associated with climate change on forest dynamics, treatment options, and wood supply at the landscape level. All this, to reach the main goal of pushing forward the adaptation of strategic forest planning to climate change.

The first research chapter (chapter 2) aimed to synthesize and analyze projected climatic changes, their implications for forest dynamics, and evaluate the applicability of novel resilience indicators and silvicultural interventions in New Brunswick's forests. The goal of this chapter was to collect climate projections for key climate variables such as

temperature, precipitation, growing degree days, freeze-thaw events, and moisture index and to consolidate in a single reference all potential effects of climate change on the landscape of New Brunswick, where the other chapters of our study are taking place. This work addressed that there is currently no cohesive, central source of information of the future climate impacts on the Acadian forest region.

The second research chapter (chapter 3) was designed to showcase a novel approach to strategic forest planning using the information provided in the first research chapter regarding climate change. Specifically, the goal was to develop climate-adapted dynamic yield tables and transition rules, informed by a climate-sensitive process-based stand-level model (PICUS; Lexer and Hönninger, 2001; Seidl et al., 2011), and integrate them into a forest management planning system (Woodstock; Remsoft, 2023). A second goal was to test if this approach enabled strategic decision-making to address future uncertainties under three climate scenarios (baseline, RCP4.5, and RCP8.5). I anticipated a significant decline in boreal-acclimated species within the landscape inventory and the harvested volume, raising concerns about wood shortages under future climate scenarios compared to the baseline.

The third research chapter (chapter 4) quantified and assessed the landscape-level impacts of having multiple management strategies available (e.g., clear-cutting, low-retention harvest, and high-retention harvest) on wood supply, financial returns, and forest risks to stressors under three climate scenarios (baseline, RCP4.5, and RCP8.5). The goal was to provide actionable insights for long-term planning and sustainability using the novel strategy introduced in the second research chapter combined with linear programming. It was hypothesised that low- and high-retention harvest would see major gains in

regeneration composition and total volume harvested within one rotation under climate change conditions due to the protective overstory cover. The study addressed critical questions, such as which treatments should be prioritized under climate change and how these decisions could affect forest attributes, including harvested volume, harvested area, and revenue from timber sales. Additionally, the chapter followed the resistance metrics outlined in the resilience section of the first research chapter to identify potential forest-related risks associated with climate warming.

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Chapter 2. The Acadian forest of New Brunswick in the 21st century: what shifting heat and water balance implies for future stand dynamics and management

Abstract

Climate change is altering the dynamics of New Brunswick's forests. To mitigate the effects of climate change, it is crucial to account for future uncertainties in climate projections and natural disturbance trajectories when designing forestry practices. This paper presents the projected changes in key climatic drivers for New Brunswick's forests, examines the impacts of climate change on forest stand dynamics, and reviews adaptive silviculture tools for climate change adaptation.

By 2071-2100, a projected 4-6°C increase in mean annual temperature will lead to a 39-77% rise in growing degree days and a reduction in summer atmospheric water balance by 48-79mm across New Brunswick. Foresters should anticipate a doubling of annual area burned, the northward migration of spruce budworm (*Choristoneura fumiferana* (Clemens)), and the introduction of novel insects and diseases. Forest simulation models project a severe decline in boreal tree species abundance, including a 50% decline in balsam fir (*Abies balsamea* (L.) Mill) and black spruce (*Picea mariana* (Mill) B.S.P.), offset by an increase in temperate species, notably red maple (*Acer rubrum* L.; +200%) and American beech (*Fagus grandifolia* Ehrh; +135%). Forests in the highlands and lowlands ecoregions, with 40-50% and 15-30% spruce and balsam fir composition respectively, are particularly vulnerable.

To limit climate change effects on forest values, foresters must prioritize climate resiliency in their management plans. Strategies should aim to maintain the capacity of forests to provide goods and services under changing climatic conditions, both for humans and for ecosystems. Forest thinning enhances stand productivity and resilience, while shelterwood and two-age harvest balances timber production with diversity. Clear-cutting, establishes younger, more vigorous forests with higher carbon sequestration potential. Assisted migration offers promise in helping threatened tree species to remain present on the landscape and contribute to species richness.

Climate change will have a significant impact on New Brunswick's forests, leading to changes in key climatic drivers, increased risks of disturbances, and a shift towards more temperate tree species. However, there are existing adaptation strategies available. It is crucial to consider future climate related risks when designing and evaluating forestry practices, as this is essential for mitigating the effects of climate change on forest values and ensuring the continued provision of forest goods and services over time.

Keywords: climate change, adaptive forest management, climate moisture index, composition shift, natural disturbances, climate projections, forest resilience

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2.1 Introduction

Climate change is altering the structure and function of forest ecosystems globally and the frequency, severity, and extent of natural disturbances (e.g. fire, insect outbreaks, droughts, and windthrow; Allen *et al.* 2010). To maintain the production of goods and services we derive from forests, modern foresters are tasked with accounting for future climate change impacts on forest stand and landscape dynamics in their management plans (Dale *et al.* 2001). Key to maintaining this production and ecosystem services (e.g., timber, carbon sequestration, wildlife habitat, etc.) in a changing climate is the maintenance of forest conditions that are resilient to change (also known as resilient forests; Messier *et al.* 2019). Forest resilience refers to the ability of a forest ecosystem to withstand and recover from disturbances, such as wildfires, insect outbreaks, extreme weather events, or human interventions, while maintaining its essential functions and structure. It involves the capacity of forests to absorb and adapt to changes (Nagel et al. 2017; Messier et al. 2019). The concept of forest resilience can provide a useful perspective from which to evaluate the suitability of forest management strategies over time, especially under climate change (Bryant *et al.* 2019). Challenges in applying this concept are 1) establishing what forest stand conditions are resilient to change, and 2) developing silvicultural approaches to guide the forest toward these conditions. Most resiliency studies often focus on single disturbances in a particular forest type, whereas forested landscapes are generally subject to multiple disturbance types (Seidl et al. 2017; Taylor et al. 2020b). Hence broader knowledge of forest resilience is limited. However, resiliency studies can be used to build distinct forest resilience indicators to inform planning models. Resilience indicators are quantitative or qualitative measures used to assess the ability of a forest ecosystem to

withstand and recover from disturbances (Bryant et al. 2019). These indicators provide insights into the health, adaptability, and overall robustness of a forest, enabling forest managers and researchers to monitor and evaluate its capacity to maintain ecological functions and services over time. Forest resilience indicators may include measures of biodiversity, species composition, forest structure, regeneration capacity, soil health, carbon storage, and the presence of key ecological processes (Dymond et al. 2015; Bryant et al. 2019). By monitoring these indicators, stakeholders can make informed decisions and implement appropriate management strategies to enhance the long-term sustainability of forest ecosystems.

In the province of New Brunswick, Canada, forests cover 84% of the provincial land area (Nadeau, *et al.* 2008) and the forest industry generates 1.7 billion dollars annually (GDP) from pulp and paper and other wood products manufacturing (Forest NB 2018). New Brunswick is part of the Acadian forest region (Rowe 1972), a unique ecological transition zone that bridges boreal forests to the north and temperate forests to the south. As a result, many constituent tree species are at their extreme northern or southern geographical range limits. Such transition zones are considered highly sensitive to climate change (Fisichelli et al. 2014; Evans and Brown 2017). The Acadian forest is composed of approximately 65% softwood and 35% hardwood tree species but dominated by balsam fir (*Abies balsamea* (L.) Mill), black spruce (*Picea mariana* (Mill) B.S.P.), red maple (*Acer rubrum* L.), trembling poplar (*Populus tremuloides* (Michx.)), and balsam poplar (*Populus balsamifera* (L.)).

Addressing regional climate change impacts requires an understanding of how heat and moisture are projected to change over time. Mean temperatures in New Brunswick

have increased by over 1.5ºC since the early 20th century (1900-2022; NOAA 2022). These elevated temperatures have caused reductions in water availability by increasing evapotranspiration by 1 mm year^{-1} over the 1960-2000 period (Fernandes *et al.* 2007) and have amplified the growing season length by over 20 days (Zhang *et al.* 2019). These trends are expected to accelerate over the next century (Zhang *et al.* 2019). Regional forest projections using the stand model PICUS (named after a Roman god of the forests) predict reductions of 25-60% in the growth of dominant boreal species in the coming decades, which will not be compensated by increasing growth in temperate species (Boulanger *et al.* 2017; Taylor *et al.* 2017). This net growth reduction will cause commercial species aboveground biomass to drop by over 25% by the year 2100 across the region under the high emission scenario, RCP 8.5 (Brecka *et al.* 2020; Taylor *et al.* 2017). A portion of decline in commercial tree biomass is likely to be attributed to the projected productivity gains in some shrub species (e.g., leatherleaf (*Chamaedaphne calyculata* (L.) Moench), Labrador tea (*Rhododendron groenlandicum* (Oeder) Kron & Judd)) in the region (Ward et al. 2019), raising serious wood supply concerns.

A growing body of evidence suggests future productivity rates and natural disturbance dynamics are shifting away from historical baselines (McLain and Lee 1996; Taylor *et al.* 2020b). Establishing successful silvicultural strategies that guide forest conditions that are resilient to these changing dynamics requires large scale collaboration and intensive monitoring systems (Noulèkoun et al. 2021). Various forms of "adaptive silviculture to climate change" are currently being tested on multiple sites across the United States (e.g., Knapp *et al.* 2021; Lu *et al.* 2014; Nagel *et al.* 2017) and more extensively in the Canadian boreal forest (e.g., Sang *et al.* 2019). Several possible adaptive silviculture

techniques are gaining interest, including (1) assisted tree species migration, i.e. the human-assisted movement of tree species and genotypes in areas outside of their known geographical range to overcome slow natural dispersal (Dumroese 2013); (2) thinning (pre-commercial and commercial), used to manage composition toward increasingly climate resilient species, impacting density to promote growth and survival of selected trees (Navarro-Cerrillo *et al.* 2019); and (3) shelterwood and two-age harvesting treatments, aiming respectively at an even and two-aged class structure while using the canopy of mature trees to act as physical buffer protecting the under story against the shifting climate (Wang *et al.* 2015).

The purpose of this study is to (1) summarize and report on projected changes in climatic variables relevant to forest management across New Brunswick's forests; (2) review projected changes in the structure, function, and dynamics of New Brunswick's forests; and (3) review novel forest resilience indicators and silvicultural interventions that are currently being promoted and tested in climate change resiliency trials, and their applicability to New Brunswick's forest.

2.2 Natural history of New Brunswick's forests

2.2.1 Climate history and physiography

The physiography of New Brunswick (Figure 2.1) was largely shaped by glaciation cycles during the past million years (Zelazny *et al.* 2007). The region belongs to the Nordic temperate sub-zone of northeastern North America and has a humid continental climate with warm summers and cold winters (averaging 16.5°C and -9°C from 1976-2005), with

a mean annual precipitation of 1100mm (1950-2013; Zhang *et al.* 2019). Local variations in climate conditions are mainly driven by topography and proximity to the ocean (Fortin and Dubreuil 2020). The Atlantic Ocean buffers seasonal temperature variations, with milder winter temperatures and colder summers along the coast. Colder annual temperatures are typically observed in the north-west highlands and uplands of the province compared to other regions (3°C and 6°C).

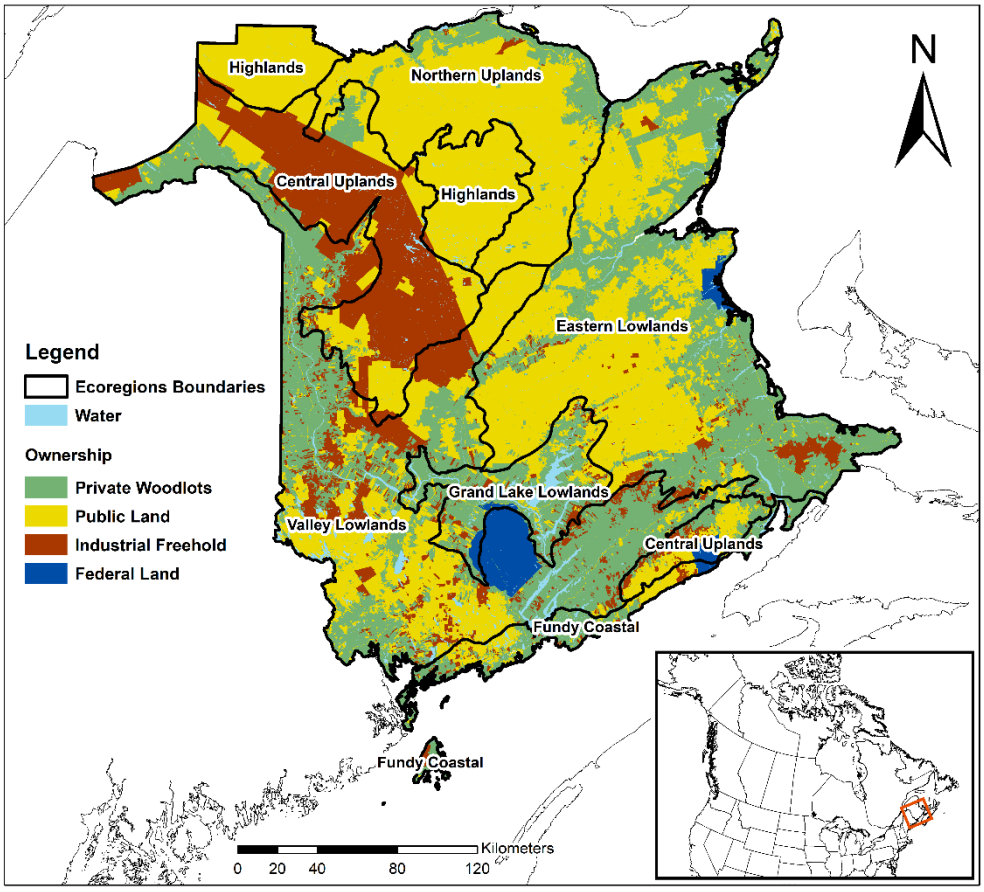


Figure 2.1. Map of study area location with land ownership provided by the Natural Resources and Energy Development Department of New Brunswick, and ecoregions (from Zelazny et al. 2007).

Dominant natural disturbances that affect New Brunswick's forests include forest fire, heavy wind, and spruce budworm (*Choristoneura fumiferana* (Clemens)). On average, from 1885-2021, one hurricane makes landfall in New Brunswick approximately every 15 years (Taylor *et al.* 2019). Other forms of windstorms also cause wide scale windthrow, such as the 1994 nor'easter that affected more than two million cubic meters of wood in the highlands ecoregion (Figure 2.1; Bourque *et al*. 2020). Spruce budworm is the primary insect disturbance in the province (Royama et al. 2005), with outbreaks occurring about every 35-years and can result in substantial host growth reduction and mortality (MacLean 1980; Johns et al. 2019; Zhang et al. 2020), e.g., 107 $Mm^3 \cdot year^{-1}$ from 1977-1981 (Sterner and Davidson 1982). In addition, several new diseases and insects that were either imported or have migrated into New Brunswick during the last century have caused serious tree damage and increases in mortality rates. For instance, Dutch elm disease (*Ophiostoma ulmi*) has killed over 90% of unprotected elm (*Ulmus sp.*) trees across the province (Magasi and Kanada 1993). The butternut canker (*Ophiognomonia clavigignenti-juglandacearum*) has reduced butternut (*Juglans sp.*) abundance over the last decade with a cankering rate of 60-75% (Gouvernment of Canada 2013). White pine blister rust (*Cronartium ribicola*) and beech bark disease (*Neonectria faginata*), both imported from Europe in the late 19th century, have infected 3% of white pine (*Pinus strobus* L.) and 99% of American beech (*Fagus grandifolia* Ehrh), respectively (Taylor et al. 2013; Gouvernment of Canada 2013). More recently, the emerald ash borer (*Agrilus planipennis*) which use ash (*Fraxinus sp.)* as its host species has been discovered in the western and southern part of New Brunswick. This exotic invasive wood borer can cause 100% host population mortality within 8-10years of arrival (Butler et al. 2022). Due to effective fire suppression efforts wildfire is

relatively uncommon in New Brunswick today (return interval of 3000 years), however historical records suggest a shorter return interval of 200-600 years was common during the pre-industrial era in New Brunswick (Taylor et al. 2020b). The most recent, significant wildfire event was the great Miramichi fire of 1825 that burned ≈1.6 M ha of New Brunswick forests (Stine 2021).

2.2.2 History of forest management and current forest state

Commercial harvesting started in the early 1700s in the region, as white pine trees were heavily harvested for ship construction (Fellows 1987). As merchantable pines became scarce in the forest, spruce species increased in importance in the mid-1800s. Both species were then supporting around 600 small sawmills in the province while eastern hemlock (*Tsuga canadensis* L.) was targeted by the leather industry for the quality of the tannins in its bark (Fellows 1987). As pulp mills were introduced in the province in the early 1900s (e.g., Bathurst Power and Paper in 1915), demand for forest products increased, which led to the harvesting of balsam fir and an increase in the size of the forestry workforce. During this time, hardwoods like yellow birch (*Betula alleghaniensis* Britton) and sugar maple (*Acer saccharum* Marsh.) were harvested only for quality lumber and veneer. The first large market for low quality hardwood only developed with the first hardwood pulp mill construction in 1970, at the same time sawmills were on a downward trend reaching near 100 mills in the late 1970s (Holloway et al. 2008). Before and during this period, harvesting levels combined with insect outbreak volume loss exceeded the total growth rate of the forest, leading to a decline in average tree size and remaining old-growth forests (less than 5% of the forested area; Mosseler *et al.* 2003). From 1976 to 2008,

industrial wood use from New Brunswick's forests has risen from 8 to 12 Mm^3 $year^{-1}$, following increases in wood imports and a greater utilization of previously marginal species like eastern white cedar and several hardwoods (Erdle *et al.* 2008). The government adopted the Crown Lands and Forest Act (C-38.1) in 1980 that established 25-year licence agreements for forest companies. The act replaced the hundreds of licences allocated on an *ad hoc* basis with ten timber licences each attributed to a licensee (six licensees remain today managing all ten licences; Martin *et al.* 2003). This legal framework, established objectives in terms of production but also in relation to forest sustainability, reducing the risk of timber shortage, and provided security to industrial companies.

Today, the forest of New Brunswick is 51% provincial public land (of which 10% is conserved), 29% small private woodlots, 18% large industrial freehold, and 2% federal public land (Figure 2.1). The provincial government, through the Natural Resources and Energy Development department, oversees management of public lands, with a harvesting rate of about 1.6% of the total public forest each year (harvest rotation of 60-65 years; NBDERD 2018).

The forest cover area of New Brunswick is approximately 22% balsam fir, 21% black spruce and 11% poplar (balsam poplar and trembling poplar included) according to the latest forest inventory (2021) made available by the Natural Resources and Energy Development department. Higher-elevation forests, located in the highlands ecoregion, are dominated by boreal species while low-elevation forests of the lowlands are occupied by a combination of boreal and temperate species (Figure 2.1). Hardwood stands, typically dominated by sugar maple, yellow birch, and American beech, are mostly located on rich, upland sites. Pure softwood stands, dominated by balsam fir, red, black, and white spruce,

are usually found down valleys and in less well drained terrains (Zelazny *et al.* 2007). Red maple acts as an opportunist species and may establish where soils are too acidic to support many other temperate deciduous species or following clearcut disturbances (Fei and Steiner 2009). Black spruce and tamarack (*Larix laricina* K. Koch) dominate forested wetlands, while jack pine is mostly located on the drier and sandier soils of eastern New-Brunswick (Zelazny *et al.* 2007).

Using large scale mechanical operations, softwood stands (dominated by spruce, fir, and jack pine) are mostly treated with even-age silviculture systems using clear-cutting (except in conservation areas where only partial harvesting treatments are allowed). Harvest is followed by planting in approximately one third of clearcuts on public lands, with the remaining area being naturally regenerated (NBDERD 2018). Early competition within plantations is managed via aerial herbicide application of glyphosate. All plantations, plus ~50% of naturally regenerated clearcuts, are treated with plantation cleaning and pre-commercial thinning respectively around 12-14 years of age following establishment, while around ~20% of clearcuts remain untreated (NBDERD 2018; 2024). In contrast, hardwood stands (dominated by maple and birch) are typically managed in a way to minimize environmental impacts and ensure natural regeneration. These low impact treatments are known to include single-tree selection for high quality stands, and shelterwood for lower quality ones (NHRI 2020). Conducting a single tree selection allows to maintain the overall stand quality, encourages the growth of a diversified understory vegetation, and reduce the risk to natural stressors such as wind, fires, and insect outbreaks (Raymond et al. 2018). On the other hand, less vigorous stands treated with shelterwood

help promote the development of a new, healthier, and more diverse forest cohort (Granstrom et al. 2022).

2.3 Projected climate change

2.3.1 Climate models, scenarios and variable selection

We generated monthly climate projections for New Brunswick from an ensemble of twenty-four daily Canada-wide climate scenarios made available by the Pacific Climate Impacts Consortium (PCIC) and Environment and Climate Change Canada (ECCC). Downscaling was done using the BCCAQv2 hybrid method, which combines results from Bias Corrected Constructed Analogs (BCCA; Maurer *et al.* 2010) and Quantile Delta Mapping (QDM; Cannon *et al.* 2015). The main observational dataset used to calibrate BCCAQv2 was produced by Natural Resources Canada at 300 arc second spatial resolution (1/12° grids, ~10 km) over Canada and includes daily minimum and maximum temperature, and precipitation amounts for the period 1950-2012 (Hopkinson *et al.* 2011; McKenney *et al.* 2011). Monthly data for Representative Concentration Pathways (RCP) 4.5 and 8.5 were derived from daily values and averaged over baseline 1981-2010 and future 2071-2100 periods. RCP 4.5 represents a moderate emission scenario where greenhouse gases emission (GHGE) starts to stabilize by mid-21st century and reach half of 2050 levels by 2100. On the other hand, RCP 8.5 mimics the continuous rise of GHGE throughout the 21st century making it the high emission scenario.

Climate variables were selected to reflect their documented importance in key processes driving forest stand dynamics and health. Temperature and precipitation both exert high control over tree growth, photosynthetic rates, evapotranspiration, respiration,

and general tree health. Both variables were modelled for the growing season, where they are most limiting (Babst *et al.* 2019), which is typically from June to August in New Brunswick. In addition, freeze-thaw events, and growing degree-days above 5°C (GDD) were considered on an annual basis. Freeze-thaw events are useful in predicting frost damage, as they strongly influence the growth of certain tree species like sugar maple (Moreau et al. 2020a, 2020b). Growing degree-days are closely related to forest productivity and were determined by calculating the difference between the average daily air temperature and a 5°C threshold below which biological activity ceases; the differential values are then summed for the entire year (days with an average air temperature below 5°C have a GDD of zero; Zhang *et al.* 2019).

By increasing evapotranspiration and vapour pressure deficit, increasing temperatures can exacerbate water deficit and stress in plants despite increases in precipitation (Allen et al. 2010). To estimate the evapotranspirative loss of water with warming, while accounting for changes in precipitation, we calculated a Climate Moisture Index (CMI) using minimum and maximum daily temperature, precipitation, and elevation data. The climate moisture index is widely used to estimate available atmospheric moisture with regard to forest types or tree species (Hogg *et al.* 2013). In this paper, Summer CMI was calculated as the absolute difference between precipitation and PET over June, July and August. Potential evapotranspiration was computed using Hogg *et al.* (2013) method of calculation which is based on the "simplified Penman-Monteith" (SPM) method of estimating potential evapotranspiration (PET), where monthly PE is assumed to be proportional to mean vapor pressure deficit (VPD). VPD is estimated from saturation vapor

pressure (kPa) at each monthly mean values of maximum temperature ($e^{*}T_{max}$; e = Euler's number 2.71828), minimum temperature ($e^{*}T_{min}$), and dewpoint temperature ($e^{*}T_{dew}$):

$$VPD = 0.5(e^{*}T_{max} + e^{*}T_{min}) - (e^{*}T_{dew})$$

The mean monthly $e^{*}T_{dew}$ was estimated as the saturation vapor pressure as the monthly mean value of T_{min} minus 2.5°C; we used the following equation to estimate daily PE in millimeter:

$$PE_{day} = 3.1 \cdot VPD \cdot kt \cdot \exp\left(\frac{Altitude}{9300}\right)$$

Where altitude is the site altitude (m) and k_t is a cold temperature modifier that decreases linearity from its maximum value of 1 when mean monthly temperatures are above 10°C, to 0 when they are below -5°C (Hogg et *al.* 2013):

$$k_t = \max\left(min\left(\frac{T_{mean} + 5}{15}\right), 1\right), 0$$

2.3.2 Climate projection results

Summer temperature is projected to increase by 3.5°C and 6.2°C on average under RCP 4.5 and RCP 8.5, respectively, over the 21st century (Figure 2.2A), the high emission scenario temperature prediction corresponds to the current climate in Pennsylvania (NOAA 2022; period 1971-2000). Specifically, the lowland ecoregion, including most of eastern and southern portions of the province except for the cooler Fundy coast, should experience the greatest warming under both RCP scenarios. Winter temperatures (December, January, and February) will increase by 3.8-6.6°C on average. Southern regions of New Brunswick will cope with winter average temperatures above the freezing point by the end of this century, while highlands winters will remain relatively cool (-7 to -4°C).

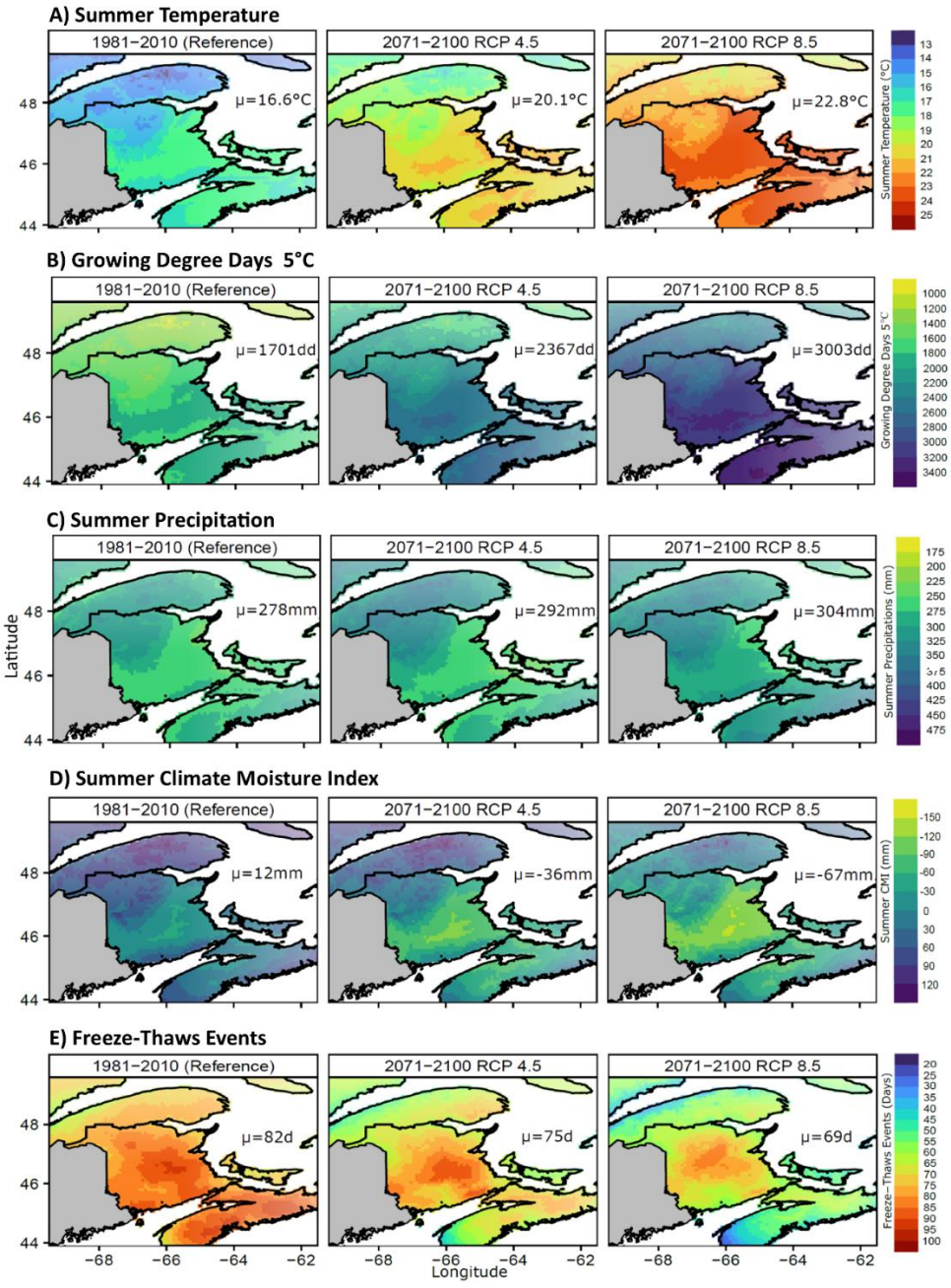


Figure 2.2. 30-year average projections of A) summer temperature, B) growing degree days 5 °C, C) summer precipitation, D) summer CMI, and E) freeze-thaws events. Baseline period 1981-2010 (left), RCP 4.5 2071-2100 (center) and RCP 8.5 2071-2100 (right). Summer months include June, July, and August. Average values are for New Brunswick only.

Increasing temperatures are projected to enhance growing degree days by 39-77% from ≈1700 to 2360-3000 degree-days on average by the end of the 21st century (Figure 2.2B), 3000 GDD roughly correspond to the 2019 values recorded in Ohio, USA. In New Brunswick, the Grand Lake lowland ecoregion is projected to achieve the highest GDD values for each RCP scenario (2800-3400 GDD). For highland ecoregions, values will range between 2200 and 2600 GDD in both RCP scenarios for the projection period. However, the magnitude of change is similar for all New Brunswick regions.

Despite these large projected increases in temperatures, summer precipitation is expected to display only moderate increases of 5-9% (13-25 mm) under the different RCP scenarios relative to the baseline summer precipitation of approximately 278 mm (Figure 2.2C). In comparison, winter precipitations should increase significantly more, with 9-31% increases (25-83 mm) relative to current levels. In the highlands ecoregion of the province, rainfall during summer is projected to stay relatively stable (325-350 mm), contrary to the lowlands, central uplands, and Fundy costal ecoregions, which are projected to experience significant increases in winter precipitation, from the baseline of 250-275 mm to projected 350-400 mm. Across New Brunswick, the mean annual precipitation will increase from baseline 1200 mm to 1250-1450 mm. The Fundy coastal ecoregion is expected to experience wetter annual conditions under RCP 8.5 (1450-1700 mm) compared to surrounding areas due to its proximity to water.

The projected increases in summer precipitation will be insufficient to counteract the negative effect of future warming on available moisture, expressed here as the CMI. For the 2071-2100 period, summer available moisture (CMI) is anticipated to decrease by 48-79 mm across RCP scenarios, because of the large summer warming (+3.5-6.2°C) coupled

with only moderate changes in summer precipitation (+13-25 mm; Figure 2.2D). The lowland ecoregions are projected to display the highest atmospheric water deficits of 60-150 mm under various RCP scenarios, while uplands and the Fundy coast will encounter limited water deficit (CMI between -30 and +60 mm) during the summer period.

The projected summer warming of +3.5–6.2 °C and modest precipitation increases of +13–25 mm under RCP4.5 and RCP8.5 align closely with national-scale analyses (Vincent et al. 2018; Abdelmoaty et al. 2025; Zhou et al. 2018). Regionally, New Brunswick has already experienced rises in potential evaporation of approximately 1 mm yr^{-1} during summer during the 1979–2016 period (Li et al. 2020), confirming an upward baseline trend in PE which drives the decrease in CMI reported here. Under RCP8.5, Tam et al. (2024) projected a summer PET increase of about 61 mm by 2071–2100, which falls within our modelled CMI decline of 48–79 mm. Moreover, projections using various PET formulations (Dallaire et al. 2021) consistently predict >30 % increases in evapotranspiration under future warming (RCP and time period), particularly in central and eastern Canada, which also correspond to the 27-54% increase in PET projected here. This confirms that temperature-driven PET rises will outpace precipitation gains and exacerbate summer moisture deficits (Dallaire et al. 2021).

Freeze-thaw events, defined here as the number of days when air temperature fluctuates above and below 0°C, should not increase in the future. In fact, freeze-thaw events are projected to display a marginal decrease in frequency by the end of the 21st century, from 82 days (baseline) to 79-69 days in 2071-2100 (Figure 2.2E). The lowlands ecoregion of New Brunswick that are currently more susceptible to freeze-thaw events should remain equally susceptible under RCP 4.5, but climate forcing under RCP 8.5

projects that the area of vulnerability will shift toward the central highlands of the province. Northeastern New Brunswick will be least affected, while the southern part of the central uplands ecoregion will display the highest occurrence of freeze-thaw events.

2.4 Climate change impacts on New Brunswick forests

2.4.1 Direct effects on forest composition and productivity

Forest tree species are estimated to have had a maximum natural migration velocity of 0.5km·year^{-1} historically following the retreat of the last glaciation, which is slower than the 3-5 km·year^{-1} estimated to keep pace with climate change induced displacement of their adequate climate zones, leading to maladaptation (Sittaro *et al.* 2017). Most simulation models of forest dynamics agree that boreal tree species abundance will substantially decline to the benefit of temperate species under climate change in New Brunswick, as the southern edge of their range shifts northward (Figure 2.3; Bouchard *et al.* 2019; Boulanger *et al.* 2021; Brecka *et al.* 2020; D'Orangeville *et al.* 2018; Taylor *et al.* 2017). More specifically, the relative abundance of balsam fir and black spruce is projected to decline by as much as 50%, while jack pine may decline by 25% by 2100 under RCP 8.5 (Taylor *et al.* 2017). The rate of decline is projected to be marginal at first, but then gradually increase by 2050, facilitating increases in the relative abundance of temperate tree species. Notably, red maple is expected to double its relative abundance to represent 30% of the New Brunswick forest composition by 2100 (without considering current migration rates; Brecka *et al.* 2020, Taylor *et al.* 2017). American beech (+135%) and white pine (+35%) are also projected to display large increases in abundance under similar scenarios during

the same timeline (Taylor et al. 2017), although the long-term effect of ongoing beech bark disease remains poorly understood. The fate of other temperate species like sugar maple is unclear. Some studies project limited changes in sugar maple distribution over the next century (Steenberg *et al.* 2013; Zolkos *et al.* 2015), while others predict a decline due to increasing competition by American beech (St-Jean *et al.* 2021) and climate anomalies (Moreau *et al.* 2020). For yellow birch, model projections for the Acadian forest region range from steady decreases starting in 2040 (Bouchard *et al.* 2019) to 25% increases (Taylor *et al.* 2017). However, models that account for harvesting impacts under climate change predict significant declines in yellow birch abundance (Boulanger *et al.* 2021; Steenberg *et al.* 2013). The general shifts in abundance are considered largely the result of changes in the competitiveness between tree species, thus modifying demographic rates which have strong control over the success or failure of a species establishment (Swenson et al. 2020).

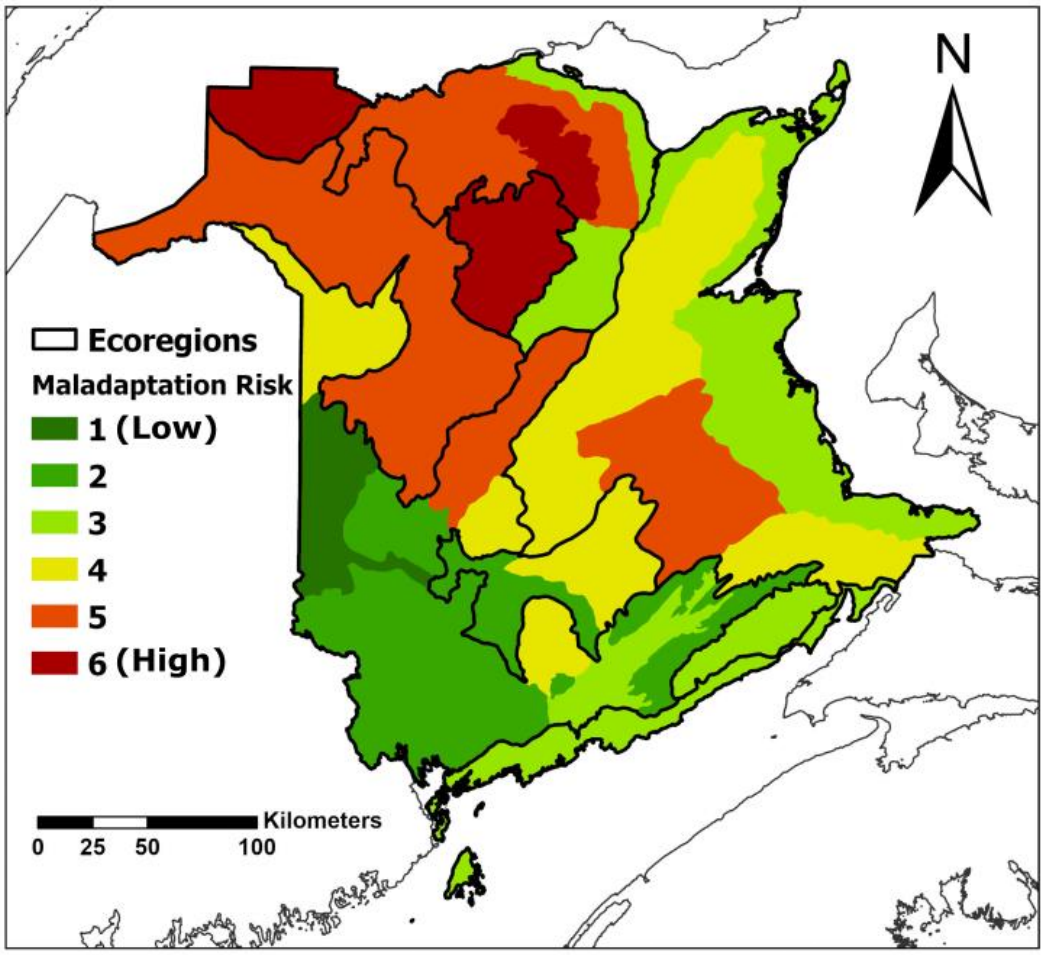


Figure 2.3. New Brunswick forest maladaptation risk based on the relative abundance of tree species projected to decline under climate warming (balsam fir, black spruce, white spruce, tamarack larch, jack pine, and white birch), modified from Zelazny *et al.* (2007). Note: maladaptation risk 1= <10%, 2 = <20%, 3 = <30%, 4 = <40%, 5 = <50%, 6 = >50% in relative abundance.

Among the few studies projecting climate change impacts on tree species composition in the New Brunswick forests, Taylor et al. (2017) used an individual tree-based model, PICUS, which projected a 6-42% decline in boreal species growth by the end

of the 21st century under the RCP 4.5 and 8.5 climate forcing scenarios. In contrast, the same study predicts stable growth rates of temperate species until around 2050, which then increases drastically during the 2050-2100 period under RCP 8.5, shifting from an average of 4 to 7 $m^3 \cdot ha^{-1} \cdot year^{-1}$. The temperate species growth increase is mainly driven by hardwood species American beech, red maple, red oak, and white ash (*Fraxinus americana* L.), when no disturbances are considered. Overall, moderate warming of New Brunswick could be beneficial to forest productivity until the mid 21st century, when gains in growth of temperate species will no longer offset growth reductions in boreal species resulting in a net decline in forest productivity (D'Orangeville *et al.* 2018; Molina *et al.* 2021).

The boreal species which are projected to decline under climate change are not equally distributed across New Brunswick (Figure 2.3). The highlands as well as the central and northern uplands ecoregions will be most severely impacted, as 45-55% of their landscape is covered by balsam fir and spruce (Figure 2.3). Eastern lowlands display moderate risks in general, but higher black spruce components increase the maladaptation risk in some locations (Figure 2.3). Balsam fir and white and black spruce, considered at-risk species, are in lower abundance in south-western New Brunswick, where sugar maple, beech, aspen, and yellow birch are more common, and at-risk species represent less than 20% of total forest cover (Figure 2.3).

2.4.2 Indirect effects of climate change from natural disturbances

Evidence suggests the frequency and severity of some natural disturbances will increase over this century by up to 10-15% relative to the 1981-2021 baseline by 2100, wind, fires, and drought are expected to deal the biggest damages while spruce budworm

survival decreases steadily south of its range as climate warms (Boucher et al. 2018; Taylor et al. 2020b). Brecka *et al.* (2020) conducted a wide-scale study projecting wood supply under different climate change scenarios using the landscape model LANDIS-II in eastern and central Canada. In all scenarios and locations examined, forest biomass lost to fires and drought increased over the 21st century, especially under RCP 8.5; to a point where biomass lost to harvest and natural disturbance exceeded overall forest growth. This threshold was reached sooner in central Canada where tree diversity is lower, fire disturbance rates are higher, and drought is more severe compared to eastern Canadian forests.

Drought is associated with severe growth reductions which can impact carbon storage, wood supply, and wildlife habitat (Brzostek *et al.* 2014; D'Orangeville *et al.* 2018). Drought-induced tree mortality is less common in eastern Canada compared to drier regions of central Canada, where drought-related forest mortality has increased 4.7% year^{-1} in recent decades (Peng *et al.* 2011). Sánchez-Pinillos *et al.* (2022) suggests that drought-induced mortality will increase in eastern Canada with higher frequencies of low-intensity drought. Moreover, the negative effects of drought can last for many years (Scharnweber *et al.* 2020) and predispose trees to other stressors like insects and diseases (Anderegg et al. 2015; Broom 2023).

Increasing temperatures and moisture deficits should also exacerbate fire risks (Boucher *et al.* 2020; Boulanger *et al.* 2013). Not accounting for historical and future fire suppression efforts, the area burned across New Brunswick should increase from a baseline (1990-2021) of 1000 ha·year^{-1} to 2000-3000 ha·year^{-1} (Boucher *et al.* 2020; CCFM 2021). In southern and northern New Brunswick, where conditions are warm and dry, the annual

area burned is projected to be four and two times higher than current level, respectively (Boulanger *et al.* 2013). However, these increases could be partially offset by fire suppression efforts as well as the projected increase in the proportion of hardwoods, which can reduce fire propagation rates by up to 50% in these areas (Boulanger *et al.* 2017; Terrier *et al.* 2013).

Spruce budworm is also a major natural disturbance agent of spruce and fir forests in eastern North America, including the Acadian forest (MacLean 2016). Climate change is projected to shift the range of spruce budworm northwards (Taylor et al. 2020b). Outbreaks in the extreme northern part of New Brunswick are projected to lengthen by 2-4 years and result in 15% more defoliation in 2081-2100 period relative to the 1981-2010 period (Gray 2013). To the contrary, warming could reduce the severity of future infestations by 40-50% (7-10 year reduction in severe defoliation) in southern New Brunswick by mid-21st century (Gray 2013; Pureswaran *et al.* 2019), but uncertainties remain due to expected shifts in spruce phenology with warming (Bellemin-Noël *et al.* 2021). Other insects and pathogens, historically constrained to the south of New Brunswick by cold climate, such as hemlock woolly adelgid (*Adelges tsugae* Annand), may migrate north with warming, thereby facilitating the establishment of novel forest pest species (DeSantis *et al.* 2013; Russo *et al.* 2019).

Wind events are important drivers of gap-phase stand dynamics in New Brunswick's forests, but can also cause major windthrow, producing significant tree mortality, increasing forest management complexity (Klaus et al. 2011; Taylor et al. 2020b). Wind events can be classified into two main categories: 1) tropical cyclones, characterized by sustained wind speeds of at least 104 $km \cdot h^{-1}$, and 2) windstorms, encompassing a wide

range of non-hurricane winds such as extratropical cyclones and convective storm cells. Among these categories, tropical cyclones inflict the most significant damage to forests due to their sheer force and extensive spatial and temporal coverage, in comparison to non-hurricane storms. However, these events are relatively rare, occurring approximately once every seven years in Atlantic Canada, with approximately 25% of the affected area experiencing severe windthrow (Taylor et al. 2019, 2020b). On the other hand, convective storm cells cover relatively smaller areas ranging from tens to hundreds of square kilometers, resulting in windthrow events affecting small, dispersed patches of 100-1000 m^2, or even extending over hundreds of square kilometers. Now that suppression of fire and insect outbreak control is effective, wind has become the dominant disturbance in Atlantic Canada.

Among the Acadian forest tree species, balsam fir is one of the most susceptible to windthrow due to its shallow rooting habit, weak anchoring, and its crown and branching architecture which acts as a sail (Ruel 2000; Taylor et al. 2019). While wind speeds are forecasted to increase only marginally (< 3%), projected soil warming may reduce the anchoring benefit of frozen soils, leading to an increase from 3 to 30% of balsam fir stands impacted by windthrow (Bourque *et al.* 2020). However, increase in windthrow risk may be offset by the reduction in balsam fir abundance projected by the end of the 21st century, leading to an overall decline in windthrow (Saad *et al.* 2017).

2.5 Resiliency indicators and management solutions for climate change

The sustainable production of goods and services to meet society's needs is central to the objectives of forest management. However, increasing risks and uncertainty associated with climate change is contributing to complexity of this already complex process. Promoting climate change resilient forest landscapes requires a good understanding of stand attributes that mitigate these risks (e.g., Bryant *et al.* 2019; Dymond *et al.* 2015). In this section, we attempt to summarize the forest landscape attributes that have been linked with resiliency to climate change and propose stand interventions to maximize them. We acknowledge that the current state of knowledge of these indicators in New Brunswick is limited, which prevents the development of quantitative thresholds in stand attributes that have been identified to promote resilience and can be integrated into forest planning models to manage for climate change.

2.5.1 Resilience indicators for climate change

Diversity in forest tree species plays a critical role in enhancing the capacity of stands to cope with changing climatic conditions and disturbance regimes (Jalonen et al. 2018; Nef et al. 2021). For instance, during insect outbreaks, more diverse stands have been observed to experience reduced defoliation compared to less diverse stands (Hisano *et al.* 2018). This applies not only to species diversity but also to intraspecific genetic diversity, which positively impacts productivity, natural regeneration success, and resistance to pests (Tito de Morais et al. 2020). Natural forests with higher species diversity have also demonstrated superior resistance to disturbance, offering enhanced resilience against external pressures (Table 2.1; Jactel et al. 2017). Furthermore, at the landscape level,

diversity in stand structures and composition acts as an insurance against climate change impacts (Messier et al. 2019).

Table 2.1. Resilience indicators for three disturbance agents frequently occurring in the Acadian forest (note: ↓ = lower is better, ↑ = higher is better, ha = hectare, m3 = meters cube).

Disturbance agent	Indicator	Resilience effect
Fires	Area of 0-29 years old forest of all types (ha)	↑
	Area of 30 + years old pure deciduous and mixed-deciduous (conifer < 50%; ha)	↑
	Area of 30 + years old pure coniferous and mixed-coniferous (conifer > 50%; ha)	↓
Insects/Pathogens	Tree species diversity within a stand	↑
	Area of monospecific stand (> 80% of basal area occupy by the same species; ha)	↓
	Volume of susceptible species to insects and pathogens (m^3)	↓
Drought	Area thinned (40-70% basal area removed) with time since thinning under 40 years (ha)	↑
	Abundance in drought tolerant species including eastern white pine, red oak, white ash, and red spruce (ha)	↑
	Ratio of total forested areas (ha) over total area clearcut (ha) younger than 15 years (ratio)	↑

Projected increases in fire risk, resulting from higher temperatures and dryer conditions, also present challenges for forest resilience (Boulanger *et al.* 2013; Wang *et al.* 2015). Over 95% of fires in Atlantic Canada start by human ignition (Taylor et al. 2020b). If forest management practices are not adapted and foresters not careful when working in the woods, this may lead to some decrease in forest productivity and higher fire suppression costs (Table 2.1; Hope *et al.* 2016; Janowiak *et al.* 2018). The flammability of stands varies

with stand characteristics, as hardwood-dominated and young coniferous stands (0 to 29 years) generate less flammable material compared to mature coniferous stands (30 + years of age; Bernier *et al.* 2016). Conifer-dominated stands also experience two-to-five-times higher fire occurrence, posing risks of understocking and regeneration failure, particularly for boreal species at their southern distribution limit (Hart *et al.* 2019; Stevens-Rumann *et al.* 2018). Conversely, certain species like white pines, with a broader distribution south of New Brunswick, may exhibit different responses.

Promoting drought-adapted species is crucial for building climate-resilient stands and forests. Species such as oaks, characterized by high hydraulic resistance to embolisms, display increased competitiveness and growth even during drought conditions (McDowell *et al.* 2008). Some tree species, including white ash, eastern white pine, and jack pine, exhibit an earlier growth phenology, allowing them to concentrate growth during periods of abundant water early in the growing season (Table 2.1; Pearson and D'Orangeville 2022; D'Orangeville et al. 2022). At the stand level, potential drought effects can also be temporarily mitigated through lower crowding, which allow the redistribution of available water to a reduced number of trees. Commercial thinning trials in a 26-year-old Norway spruce (*Picea abies* (L.)) plantation lowered stand-level transpiration by 25-50% (Gebhardt *et al.* 2014), increasing tree-level transpiration by 30-50%, an indicator of high photosynthesis and growth. However, the beneficial effects of thinning are limited in duration, typically lasting 20-40 years post-treatment, as larger trees in thinned stands become more sensitive to drought (Table 2.1; Manrique-Alba *et al.* 2022). Clear-cutting and clearing areas also have implications for water loss, reducing soil water holding capacity and retention through the reduction of organic material, elevated soil

temperatures, and lower transpiration rates (Bawafi *et al.* 2020). The effects of such disturbances on water runoff and retention can persist for 10-15 years, varying with seasonality (Ide *et al.* 2013).

2.5.2 Forest interventions influencing resilience to climate change

Current empirical knowledge on the effect of silvicultural interventions on forest resilience remains very scarce. In response to this knowledge gap, several adaptive silviculture trials are underway in North America. Notably, the Adaptive Silviculture for Climate Change research project is establishing a network of silvicultural trials at several locations in the United States, and one site in Petawawa, Canada (Nagel *et al.* 2017). The trials aim to compare the results of status-quo silvicultural prescriptions with novel silvicultural regimes under climate change uncertainty to guide the forest toward three different management states based on resistance, resilience, and transition (Nagel et al. 2017). These concepts provide a framework for managing forests in the context of climate change by focusing on minimizing impacts (resistance), enhancing recovery and adaptability (resilience), and facilitating shifts in composition towards more climate-resilient states (transition). Another project, the Resist-Accept-Direct framework was developed by National Park Services in the U.S. to assist managers in making informed choices about how to respond to a climate induced forest trajectory change (Schuurman *et al.* 2020). These research avenues are adopting new approaches and monitoring methods to increase the adaptability of forested ecosystems to changing climate through increased diversification, complexity, and capacity for self-reorganization of the forest (Nocentini 2015).

Building upon the current knowledge gap surrounding the effects of silvicultural interventions on forest resilience, it is of importance to explore and comprehend the potential of various intervention methods. Thinning, shelterwood and two-age cover harvest, assisted migration, and clear-cutting stand as prominent intervention methods that have garnered considerable attention from both forest industries and scientific researchers (e.g., Roy and Nolet 2018; Taylor et al. 2020a; Pelai et al. 2021; Moreau et al. 2022). Understanding the benefits, limitations, and considerations associated with each intervention method holds the key to gaining valuable insights into their efficacy and their potential contributions to fostering resilience in forested landscape (Messier et al. 2019). By delving into these interventions and critically evaluating their implications, we can pave the way towards sustainable forest management practices that optimize the resilience of forested landscapes.

2.5.2.1 Thinning

Forest thinning is a tending treatment that entails the strategic removal of trees during their early developmental stages to mitigate the intensity of competition among the remaining trees. By selectively removing certain trees, forest managers aim to guide and manipulate the composition of the stands, with the general goal of improving the overall quality of the growing stock (Ashton and Kelty 2018). Thinning has many other benefits ranging from increased stand productivity to higher resilience (Table 2.2). Among its main benefits, thinning can decrease fire risk by reducing fuel loads (Jain et al. 2020), enhance tree performance by reducing competition for resources such as water, light and minerals (Navarro-Cerrillo et al. 2019; Knapp et al. 2021), increase tree vigour to survive insect

outbreaks (Hood et al. 2016), and stimulate root development to diminish the chance of windthrow (Picchio et al. 2020; Table 2.2) However, thinning treatments should be used with caution, as poor species selection or inadequate stand structure may result in adverse effects where the risk of natural stressors become greater resulting in increased damage; Table 2.2). The main limitation of thinning is that the treatment temporarily increases the risk of wind damage to residual trees, which can worsen for older stands and tree height (Moreau et al. 2022) meaning that thinning performed in older stands without previous treatments that aim at solidifying the structure should be avoided.

Table 2.2. Overview of benefits and objectives and potential problems associated with the application of thinning in the event of distinct disturbances and in the context of climate change.

Disturbance	Benefits and objectives	Potential problems	Reference
Fire	• Intensive thinning reduces fire risks by harvesting mortality and reducing fuel availability in future years, • Reduce negative effects of severe fires, • In case of fire treated areas has a more homogenous fire behaviour.	• Rise in forest floor fuel availability immediately after thinning increasing fire risks in the short time, • A complementary understory cleaning is needed to enhance effect on reducing fire risks, • High crown/height ratio could in some forest types increase fire severity of crown burn.	Hevia *et al.* 2018; Jain *et al.* 2020; Piqué and Domènech 2018.
Drought	• Intensive thinning enhances tree performance and distributes available water to a smaller number of individuals, increasing water use efficiency.	• Increase in drought risks if only one treatment is conducted when natural mortality has been absorbed by remaining trees, increasing tree size and water demand.	D'Amato *et al.* 2013; Knapp *et al.* 2021; Navarro-Cerrillo *et al.* 2019.
Insect outbreaks	• Increased tree vigour reduces tree vulnerability to insect attacks and diminishes the risk of death in the case of an attack, • Reduced density limits the spread rate of minor to moderate outbreak to other stands, • Control residual species composition to reduce infestation risks.	• Defoliation can be higher in thinned stands but high leaf area due to enhance light conditions counterbalance the effect of elevated defoliation, • Thinned stands that have not yet responded to the treatment are particularly at risk.	Hood *et al.* 2016; Ostaff *et al.* 2006; Rossi *et al.* 2018.
Wind	• Thinning occurring at an early development stage will stimulate root development, reducing wind damage and windthrow risks, • Thinning from below has a reduced risk of wind damage.	• Late thinning usually destabilize stands because of the high wind exposure of residual trees with high height/diameter ratio, • Vulnerability due to late thinning can last up to 10 years in less productive stands, • Wind damage susceptibility improves with tree height and stand age at thinning.	Duperat *et al.* 2021; Picchio *et al.* 2020; Torita and Masaka, 2020.

Studies examining thinning effects under climate change have primarily focused on the impacts of individual disturbance agents, such as wildfires, insect outbreaks, wind, or droughts (e.g., Sohn et al. 2016; Rabin et al. 2022; Achim et al. 2022; Table 2.2). However, emerging research in the field of natural disturbance ecology suggests that under climate change, these disturbance agents are increasingly likely to interact with one another (Taylor et al. 2020b; Ruel et al. 2023). This interaction can result in complex and synergistic effects on forest ecosystems that influence the beneficial effects of thinning treatments (Moreau et al. 2022), effects that are still relatively unknown. Future research should explore the specific mechanisms and processes through which disturbance interactions influence thinning effectiveness, providing valuable insights for sustainable forest management in a changing climate.

2.5.2.2 Shelterwood and two-age cover harvesting

Shelterwood harvesting is a silvicultural method used to promote forest regeneration while maintaining ecosystem integrity. This partial regeneration harvest intervention involves a series of partial cuts spread over a short period, leading to the establishment of an even-aged cohort of regeneration while preserving canopy cover during the establishment phase (Ashton and Kelty 2018). The treatment typically comprises four phases: preparatory cut, seedling establishment cut, secondary cut, and final cut (Boulet *et al.* 2013). The preparatory and seedling establishment cuts are commonly combined in the first harvest, while the secondary and final cuts are usually grouped in the final harvest to optimize treatment costs (Boulet *et al.* 2013).

Shelterwood harvesting offers several advantages over clear-cutting, making it an ecologically valuable forest management practice. By balancing timber production with species and structural diversity, it contributes to maintaining a higher variety of tree sizes, including dead trees, which are key to enhancing resilience against climate change (Kohm and Franklin 1997; Fenton et al. 2013). The presence of dead trees within the canopy provides habitat diversity and food availability for numerous faunal species, supporting overall ecosystem health (Kohm and Franklin 1997). Furthermore, shelterwood harvesting has been shown to foster vigorous and dense regeneration compared to clearcut sites, as evidenced in a Czech Republic experimental study conducted in even-aged Scots pine (*Pinus sylvestris* L.) stands (Brichta et al. 2020). This characteristic of shelterwood harvesting makes it a valuable tool in promoting forest regeneration and recovery. In addition to its positive impact on biodiversity and regeneration, the progressive nature of the shelterwood regeneration process aligns with five out of the six principles of climate change adaptation, as identified by Brang et al. (2014). Moreover, shelterwood harvesting has proven effective in managing invasive species, such as the ongoing American beech invasion of shade-tolerant stands in eastern North America (Roy and Nolet 2018). The treatment is restoring the balance between tree species and mitigating the adverse effects of invasions (Roy and Nolet 2018). Further, shelterwood harvest systems that retain at least 50% of the initial basal area buffers environmental stress on seedlings increasing their survival during the first years of establishment (Mallik *et al.* 2013).

The two-age continuous cover management system shares similarities with shelterwood, as both approaches emphasize maintaining canopy cover during regeneration. However, the two-age continuous cover system is distinctive in its focus on always

sustaining two distinct age classes (NHRI 2020). Its growing popularity stems from the continuous supply of forest products while preserving the protective canopy benefits, buffering regeneration from external climatic conditions (Harrington et al. 2022). Being a continuous cover method, this approach offers unique forest values with its more complex vertical and horizontal structure, a feature that cannot be solely provided by shelterwood or clearcut harvests positively affecting resilience over the landscape treated with a mosaic of these different treatment (Bose et al. 2020; Girona et al. 2023).

The implementation of shelterwood and two-age cover harvests in forest management has demonstrated numerous benefits, yet it is essential to acknowledge and address potential drawbacks associated with these approaches. The establishment of an even-aged regeneration cohort may be hindered by inadequate canopy gaps, limiting successful natural regeneration, and potentially affecting forest biodiversity and the rate of success of the treatment (Bose et al. 2023). Moreover, the retention of residual trees could create favorable conditions for pests and diseases, posing challenges to stand health if not alleviated by high landscape biodiversity (Girona et al. 2023; Bose et al. 2023). On the other hand, partial harvests demand intricate management, leading to higher operational costs and reduced timber output during selective harvesting (Soman et al. 2019). The success of these methods and the level of resilience gained are highly dependent on the selection of appropriate trees at the time of harvest and the extent of damages to residual stems (Moussaoui et al. 2020).

2.5.2.3 Clear-cutting

Clear-cutting, a logging treatment involving the complete removal of trees in a specific area, has received significant attention in forest management strategies amid the context of climate change, primarily due to its potential implications for carbon sequestration, forest regeneration, biodiversity, and its indirect impact on conservation. In the specific context of New Brunswick, clear-cutting's effects on regeneration are variable, with a tendency to favor fast-growing and shade-intolerant species (Taylor et al. 2020a). Notably, red maple, white birch, and poplars have been identified as the most opportunistic merchantable tree species, although birches and poplars face challenges due to their boreal traits in the changing climate (Taylor et al. 2017). Clear-cutting is particularly suitable in situations where natural regeneration is limited or when certain tree species require open spaces for growth that cannot be achieved through alternative treatments (Ashton and Kelty 2018). Furthermore, clear-cutting, followed by reforestation, results in the establishment of younger, more vigorous forests with a higher potential for carbon sequestration compared to older, mature forests. Rebane et al. (2020) demonstrates that naturally regenerated boreal forests following clear-cutting transition from being carbon sources to carbon sinks within 5-6 years post-harvest. Additionally, clear-cutting can aid in the control of pest and disease spread, thereby safeguarding the health of adjacent forest stands (Hartshorn 2021; Tsikas and Karanikola 2022). Importantly, the intensive nature of clear-cutting, when followed by plantations, indirectly contributes to the conservation of forest areas by concentrating harvest activities in limited portions of the landscape (Côté et al. 2010; Himes et al. 2022). This land zoning approach, akin to those being implemented in

Nova Scotia and Quebec (Thuot et al. 2005; Lahey 2019), holds promise for enhancing conservation efforts in the region.

However, it is crucial to acknowledge the potential drawbacks and negative impacts associated with clear-cutting, particularly in the context of climate change, as highlighted in various studies. Clear-cutting is generally regarded in the literature as a transitional treatment rather than one that strictly promote forest resiliency (Bataineh et al. 2013; Nagel et al. 2017; Ibarra et al. 2017). Firstly, clear-cutting eliminates the protective cover provided by trees, exacerbating the negative effects of climate change-induced heat and water stress (Boros et al. 2019; De Lombaerde et al. 2022). This practice tends to simplify the species composition and structural diversity of the forest, resulting in even-aged monospecific stands, especially when plantations are established (Kusumoto *et al.* 2015). At the landscape level, clear-cutting is likely to contribute to habitat fragmentation, jeopardizing numerous species that rely on complex forest structures and diverse microhabitats, which are lost through clear-cutting (Lehmkuhl and Ruggiero 1991; Fortuin and Gandhi 2021). Furthermore, the complete removal of on-site trees eliminates the root systems that play a crucial role in soil stabilization, leading to increased soil erosion and a subsequent decline in soil fertility for subsequent cohorts (Fielding et al. 2022).

In New Brunswick, planted clearcuts represent around 33% of clearcut areas, and undergo mechanical site preparation followed by the plantation of predominantly white and black spruce (NBDERD 2018), It is worth noting that these two species have been found to exhibit low tolerance to future warming (Taylor et al. 2017). The response of planted trees to climate change may differ from that of natural stands and populations due to factors such as vegetation control and the superior growth traits of the planted trees,

which have been developed through extensive tree breeding programs (Ennos 2015). Furthermore, plantations generally have significantly shorter rotation periods compared to natural forests, which reduces their vulnerability window to natural stressors and, consequently, their susceptibility to climate change (McEwan et al. 2020). However, there are important knowledge gaps concerning how well the white and black spruce genotypes in these plantations can respond favorably to climate change under tree improvement programs.

2.5.2.4 Assisted migration

Assisted migration is the human assisted movement of tree species and populations in response to climate change. The practice consists of matching climates in which seed sources evolved with near future climates for plantation sites (Pedlar *et al.* 2011). It is also a key silvicultural practice to help tree species that are threatened by rapid climate change to overcome reductions in regeneration and growth and increasing mortality attributable to climate changes (Barrette *et al.* 2021; Löf *et al.* 2019). Assisted migration is used to artificially speed up the migration of warm-adapted populations, increase species diversity, and to promote better adapted species, ensuring a sustainable future productivity in the managed forest (Pelai *et al.* 2021). One potential challenge of assisted migration is the uniqueness of each species regarding their local adaptation and phenotypic plasticity, but also the capacity of genotypes to not only tolerate future, warmer, conditions, but also current, colder conditions, making assisted migration risky and research intensive (Sáenz-Romero *et al.* 2021). In the context of the 21st century climate change projections, assisted migration strategies will have to be implemented based on species-specific vulnerabilities

to environmental changes and industrial needs (e.g., spruce *spp.* in New Brunswick). Consultations with First Nations are important when implementing assisted migration mainly because first nations possess rich traditional ecological knowledge that encompasses a deep understanding of local ecosystems that have a high chance of enhancing the effectiveness and success of assisted migration efforts (Berkes et al. 2000). Collaboration with these nations creates opportunities for shared decision-making, co-management, and mutual learning while respecting the deep cultural connections that trees are playing in their traditional practices (Whyte et al. 2019).

Currently, assisted migration is mostly being used and tested only for research in eastern Canada, the industrial implementation of this practice is still pending in almost all locations due to research and seed source limitations (Klenk Larson 2015). Some species are more responsive to assisted migration than others because they are less sensitive to warming and therefore have a better survival rate in a colder environment when being migrated. Typically, the natural distribution range of species is a good indicator of such ability and tolerance to climatic change, widespread distribution ranges show an ability to develop under a wide range of climate conditions (e.g., red spruce vs red oak; Guan *et al.* 2021; Williams and Dumroese 2013). Some assisted migration trials currently in place in western Canada reveal that the plantation of white spruce (*Picea glauca* Voss.) from seed sources 3°C warmer than plantation sites can mitigate the negative impact of climate change on productivity (Sáenz-Romero *et al.* 2021). Similar trials are conducted in Ontario and Quebec where southern seed provenances are tested to be used further north (e.g., Lu *et al.* 2014; Prud'homme *et al.* 2018). Species ecological niches must be carefully studied before a species is planted and introduced into a new region to avoid large-scale

regeneration failure from different factors like frost hardiness, competition, predators, etc. (Park *et al.* 2014; Sebastian-Azcona *et al.* 2019). It is important to note that southern population migration can lead to "decoupling" with seasonality in migrated regions increasing the risk of early leaf unfolding leading to spring frost damage (Leites *et al.* 2019). Furthermore, deer and moose browsing susceptibility might be an important criterion in species selection given its influence on seedling survival in eastern Canada (Champagne 2021).

2.6 Conclusion

Forest conditions and productivity will significantly be altered by a 6°C increase in summer temperatures and increasingly negative CMI especially at the end of the current century. This is happening as public demand for woody material and expectations toward conservation are higher than ever. In New Brunswick, cold-adapted northern species populations will decline while warm-adapted temperate species will thrive. Adaptive silviculture for climate change programs are suggesting various management techniques that promote the forest resilience to climate change, and several trials and management efforts are already in place through the northern hemisphere. Meanwhile, resilience indicators are being developed to accurately monitor the capacity of ecosystems to cope with the range of predicted changes and to fulfil human demand for forest products and services. Thinning, shelterwood and two-age harvest, and assisted migration are important silvicultural tools identified by adaptive programs to use to create resilient forest conditions and temper climate change negative effects. However, most agencies must develop the ability to incorporate climate change and resiliency into planning and prescription

development. On the way forward, foresters and scientists need to focus on the integration and the understanding of multi-interacting stressors and management strategies rather than concentrate on singles events and solutions to understand how we can include constant environmental changes in our planning for sustainable forest management. Foresters have just begun their adaptation to this new reality, and this review is gathering tools that are essential to continue the implementation of multi-scale climate adaptive forest management.

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Chapter 3. Integrating the effects of climate change into long-term strategic forest management planning using a process-based stand model

Abstract

Integrating climate change into strategic forest management is critical for predicting forest dynamics and maintaining resource availability. However, there is currently no scientific consensus on the best approach for integrating climate change effects into strategic-level forest management planning. In this study, we propose a novel approach to incorporate climate change into a strategic forest planning model, Woodstock, using a parsimonious set of climate-sensitive stand yield tables and transition rules derived from the PICUS stand simulation model, calibrated for the Acadian forest region. To capture the dynamic effects of climate on forest growth and composition, climate-sensitive yield tables were generated for a baseline and two climate-forcing scenarios. Initial forest conditions were grouped into four age classes for each stand type, with future conditions determined by three transition periods. Stand simulations predicted a significant shift toward warm-adapted species, with red maple, white pine, and yellow birch becoming more dominant, while cold-adapted species like balsam fir and spruce declined by 2120. Under high climate forcing, the merchantable wood volume is projected to decrease by 50%, indicating potential shortages and economic risks. The incorporation of climate change uncertainty into strategic forest planning is essential to reduce the risk of overutilization of forest

resources. This research offers a novel and practical approach to integrating climate change into forest planning models.

Keywords: Woodstock, sustainability, landscape, climate forcing, stand level.

Albert, C., Taylor, A.R., and D'Orangeville, L. 2025. Integrating the effects of climate change into long-term strategic forest management planning using a process-based stand model. Can. J. For. Res. 55: 1–17. NRC Research Press. doi:10.1139/cjfr-2024-0238.

3.1 Introduction

Canada is warming at more than twice the global rate, having already reached 1.5˚C of warming since 1950 (Bush and Lemmen 2019). Warming trends are projected to persist throughout the 21st century, leading to more severe weather conditions (Flato et al. 2019). Eastern Canada's Acadian forest region (Rowe 1972) is particularly at risk from climate change, as it is an ecological transition zone linking conifer-dominated boreal forest to the north with temperate deciduous forest to the south, with many of its constituent tree species living near the edge of their climatic envelopes (Goldblum and Rigg 2010; Baldwin et al. 2020). The region is forecasted to experience significant increases in summer temperatures (+4-7˚C) with only marginal changes in summer precipitation, potentially leading to declines in atmospheric water availability and a decrease of approximately 100 mm in the summer climate moisture index by the end of the 21st century (Albert et al. 2023). Forest ecosystems in the region will be severely impacted, as balsam fir (*Abies balsamea* L.) and black spruce (*Picea mariana* Mill.) are expected to compete poorly against warm-adapted temperate species like red maple (*Acer rubrum* L.), northern red oak (*Quercus rubra* L.), and American beech (*Fagus grandifolia* Ehrh.), decreasing the overall productivity of the biome (Rogers et al. 2017; Taylor et al. 2017; Vaughn et al. 2021).

Climate change poses a major challenge to forest managers by altering wood supply in the Acadian forest region (Taylor et al. 2017; Brecka et al. 2020). One reason for this is the potential increase in the frequency and severity of natural disturbances driven by climate change, such as wildfires, insect outbreaks, and windstorms, which degrade the availability of timber (Taylor et al. 2020b; Albert et al. 2023). Another reason is related to

the effect of climate change on forest stand demographics. Tree regeneration, growth, and mortality collectively shape the productivity of stands and are all influenced by multiple interacting climatic factors such as temperature, precipitation patterns, and seasonal variability (D'Orangeville et al. 2016; Boulanger et al. 2018). Reductions in stand productivity and in overall timber supply at the landscape-level can occur when the proportion of stands negatively affected by climate change outweighs those positively affected. To account for climate change in strategic-level forest management planning, foresters require the ability to forecast landscape dynamics under climate change using models capable of incorporating the effects of climate change on stand dynamics (Taylor et al. 2009; Bettinger et al. 2016; Albert et al. 2023).

Most strategic-level forest management planning models today rely on parameters derived from empirical or process-based stand models that do not, or only partially, account for the effects of climate change on stand dynamics (e.g., OSM, ARTEMIS, TAS Simulator, FVS; Metsaranta et al. 2024). Indeed, most strategic-level forest management planning models assume a constant climate (Walters 1993; Lundholm et al. 2020) or rely on forms of climate-growth modifiers to account for climate change (e.g., O'Neill and Nigh 2011; Mathys et al. 2018; Searls et al. 2021). Growth modifiers usually take the form of simple multipliers or scalars applied to stand growth and yield tables, pushing the curve up or down depending on how the stand type is expected to respond to climate change (Pukkala 2017). However, this approach has faced significant criticism for being overly simplistic (Girard et al. 2021). For instance, the application of a single scalar that assumes a static effect of climate on all yields over time overlooks the fact that the intensity and impact of climate change on stand dynamics are expected to vary over time, leading to

inaccurate predictions (Taylor et al. 2017). Additionally, growth modifiers are typically generated from stand models that only simulate limited aspects of the effects of climate change on stand dynamics or rely on observed temporal climate-growth relationships, which are not expected to hold in the future (Metsaranta et al. 2024). Further, stand-level growth modifiers are unable to account for species-specific environmental relationships that affect tree regeneration, growth and survival, factors that also interact with climate change and are pivotal for timber projections (Girard et al. 2021; Palma et al. 2021; Giebink et al. 2022).

To address the shortcomings of simple growth modifiers, one viable alternative is the use of process-based stand simulation models (e.g., JABOWA-3, PICUS, SORTIE-ND) capable of incorporating the effects of climate change on species-specific regeneration, growth, and survival properties to generate yield tables and successional transition rules (Willis et al. 2023; Metsaranta et al. 2024). Yield tables forecast future stand conditions by providing information on such variables as wood volume, density, height, basal area; while successional transition rules describe how forest stands change over time in terms of species composition and age class structure, predicting how a forest stand will transition from one state to another following harvesting and different disturbances. Process-based stand simulation models are computational tools that model forest stand dynamics, typically at spatial scales of 100 to 1,000 square meters, by simulating many of the underlying ecological processes that drive stand dynamics (Bettinger et al. 2016; Taylor et al. 2017; Metsaranta et al. 2024). These models rely on a mechanistic understanding of how trees regenerate, grow, and respond to environmental factors such as light, water, nutrients, and temperature by explicitly modeling demographic processes such as seed

production and germination, stem growth in response to light and soil conditions, and the effects of competition from neighboring trees on survival (Taylor et al. 2009). Process-based models have historically been primarily devoted to research-oriented applications (Taylor et al. 2009) but are increasingly being considered in forest management planning to enhance our ability to incorporate the effects of climate change (Chen et al. 2018; Brecka et al. 2020; Palma et al. 2021). Because these models are independent of historic stand-level data (on which empirical-based models depend), they have greater capacity to forecast how stands will respond to novel environmental conditions, such as those posed by climate change and management strategies (Willis et al. 2023).

While process-based models can account for climate change effects on tree demographic processes, it remains highly challenging to convert their dynamic climate-sensitive outputs into inputs for strategic planning models. One of the most widely used commercial forest landscape planning models is the Woodstock Optimization Studio (Remsoft 2023), which requires inputs of all future forest stand conditions and dynamics in the form of stand type specific yield tables and successional transition rules. The model is widely used in natural resource management as a decision support system, especially in forestry, due to its optimization capacity and ability to produce a detailed schedule of actions to achieve management goals (Bettinger et al. 2016; Lantz et al. 2022). Despite its extensive use, integrating climate change details into Woodstock poses a significant challenge due to its need for deterministic and adaptable data inputs of stand yield tables and successional transition rules (Kaya et al. 2016). Adjusting these two sets of parameters to be climate-sensitive would enable Woodstock to consider the effects of climate change

in its management schedule. Such comprehensive integration of climate effects on stand dynamics has not been previously attempted (Metsaranta et al. 2024).

The objective of this study is threefold: first, to develop yield tables that adjust continuously as the climate changes and transitions rules that get adjusted based on three climate periods; second, to present an innovative method for integrating this yield and transition information into a strategic forest management planning decision support system; and finally, to impose the influence of climate change on the generation of timber and monetary returns across our planning unit (see Table 3.1 for definitions of key terms). Specifically, we demonstrate this approach using the process-based stand simulation model PICUS (Lexer and Hönninger 2001), which incorporates the effects of climate change on stand dynamics (e.g., Taylor et al. 2017). We then illustrate how outputs produced from PICUS are used to create climate-informed yield tables and transition rules (Table 3.1) that will be integrated into the decision support system Woodstock, providing the capacity to simulate the effects of climate change on forest landscape dynamics. This new parametrization is evaluated using an 87,000 ha case study forest in the Acadian forest region of New Brunswick under three climate scenarios: baseline (1981-2010 average with no change), RCP4.5 (moderate climate forcing), and RCP8.5 (high climate forcing). In each scenario, 1% of the working forest is harvested annually through clear-cutting, prioritizing stands with the greatest age-related volume declines. Three main Woodstock outputs, merchantable volume per species, stumpage revenue, and present value, will be analyzed to study the effects of integrating climate change into strategic planning and the efficiency of the developed method.

Table 3.1. Key terminology for strategic forest management and climate adaptation.

Nomenclature or Concept	Definition
Boreal species	Tree species with a boreal forest affinity, characterized by an adaptation to short growing seasons and long, cold winters.
Climate-capable stand model	A process-based stand simulation model designed to forecast forest growth and composition under varying climate scenarios.
Future stand	A stand that is forecasted to be regenerated during the strategic planning horizon.
Growth modifiers	Scalars that influence tree growth and development rates based on environmental variables, such as light, temperature, water availability, and nutrient levels.
Hardwood	Angiosperm tree species, usually broad-leaved and often deciduous.
Landscape	A larger ecological unit that encompasses multiple stands and ecosystems, often across varied topographies and land uses.
Planning horizon	The total time period over which strategic management plans are developed and their impacts simulated across the planning unit.
Planning unit	The total geographic area over which the management situation primarily occurs. Also sometimes called the management unit or management area.
Shade-intolerant	Tree species that require abundant sunlight for growth and have limited capacity to survive in shaded conditions.
Shade-tolerant	Tree species that can thrive under low-light conditions, enabling them to grow under the canopy of other trees.
Softwood	Gymnosperm tree species, generally coniferous and evergreen.
Spatially explicit process-based stand model	A type of computer-based simulation model capable of considering the exact position of each tree and that simulates numerous ecological processes, such as growth, regeneration, and mortality using sets of algorithms.
Stand	A unit of forest area containing a group of trees that share similar characteristics, such as species composition, age, and structure, and are managed as a single operating unit.
Strategic planning	The highest level of the planning hierarchy, under which tactical and operational planning occur. Strategic level planning aims at achieving broad forest management objectives over the whole planning unit, over long (multi-decade) time scales.
Temperate species	Tree species with a temperate forest affinity, typically adapted to moderately warmer climates than boreal species.
Theme	A land classification scheme used in Woodstock that describes the various conditions found throughout the landscape.
Transition rules	Directional changes in stand composition and structure as predicted by a stand model that indicate future stand conditions following disturbance (e.g., harvesting).

Yield tables	Tables that provide estimates of expected future stand conditions such as timber yield over time based on species composition, age, and site quality.

3.2 Material and methods

3.2.1 Study area

Our study area is located on the 5th Canadian Division Support Base Gagetown (hereafter referred to as 'Gagetown') in southern New Brunswick, operated by the Canadian Armed Forces (i.e. the military, not the civilians in Gagetown). The 87 000-ha forest available for harvest at Gagetown represents 62% of the total land base (Figure 3.1). The climate is temperate-continental, characterized by cold winters and warm summers, with mean January and July temperatures of -6˚C and 14˚C, respectively. The area experiences high precipitation, averaging 1200 mm annually, with a frost-free period of 215 days. Elevations range from sea level to 420 meters in the Nerepis Hills, located at the extreme south of the study area. Fertility varies considerably, from well-drained, rich floodplains to acidic podzols formed due to high average annual precipitation and humidity levels, resulting in a high diversity of tree species and site productivity across the area. Except for occasional severe blowdown events caused by windstorms (mainly post-tropical storms originating from the Atlantic Ocean) and defoliation by the spruce budworm (*Choristoneura fumiferana*), stand-replacing natural disturbances are relatively uncommon in Gagetown (Taylor et al. 2020b). Past military activities in the area have led to notable human-caused fires, burning approximately 2,500 ha over the last century, resulting in large areas being occupied by shade-intolerant young hardwood stands. Like many parts

of North America, previous forest management activities at Gagetown have been planned using the Woodstock model as a decision support system for the past decade, making it a valuable and well-understood tool for forest managers in the area (Metsaranta et al. 2024). Timber harvesting, primarily in the form of clear-cutting, has been the predominant anthropogenic disturbance on the landscape but has been limited to 410 $ha \cdot year^{-1}$ since 1985. This is because intensive forestry activities received relatively little attention during that period at Gagetown, resulting in conservative harvest levels. Other forest management activities include partial cutting (20 $ha \cdot year^{-1}$ since 1985) and precommercial thinning (75 $ha \cdot year^{-1}$ since 1985).

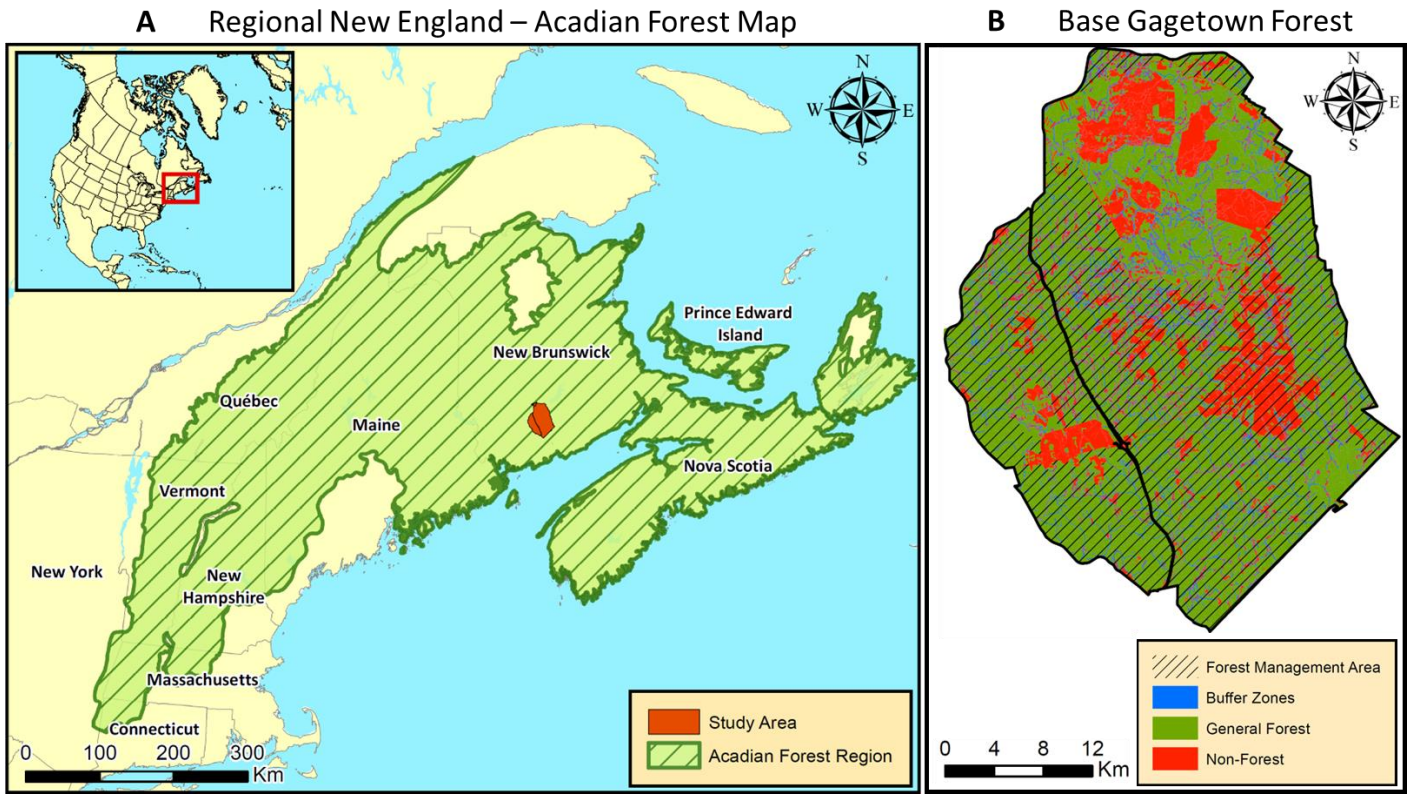


Figure 3.1. Location of the Gagetown study area **A)** in relation to the Acadian forest region (from Noseworthy and Beckley 2020 - *Borealization of the New England – Acadian forest: a review of the evidence*; Environmental Reviews: 28(3): 284-293; doi: 10.1139/er-2019-0068) and **B)** The forested landbase of Gagetown, traversed by the public highway (black line). Maps created with ArcGIS Pro v3.1.2 software using spatial data provided by the New Brunswick Department of Natural Resources and Energy Development.

Currently, in terms of volume, the Gagetown forest is 25% dominated by red maple, 22% by a mixture of red (*Picea rubens* Sarg.), white (*Picea glauca* (Moench) Voss), and black spruce, 15% by balsam fir, 8% by white pine (*Pinus strobus* L.), and 7% each by trembling aspen (*Populus tremuloides* Michx.), sugar maple (*Acer saccharum* Marsh.), and yellow birch (*Betula alleghaniensis* Britt.). Additionally, 4% is dominated by white birch (*Betula papyrifera* Marshall), 3% by red pine (*Pinus resinosa* Ait.), and the remaining 2% by species such as eastern hemlock (*Tsuga canadensis* (L.) Carrière), tamarack larch (*Larix laricina* K. Koch), eastern cedar (*Thuja occidentalis* L.), jack pine (*Pinus banksiana* Lamb.), red oak, and white ash (*Fraxinus americana* L.). The Gagetown forest was stratified into twelve stand types and inventoried by LiDAR in 2018 by the Department of Natural Resources and Energy Development of New Brunswick (DNRED). The LiDAR forest inventory had an initial resolution of 20m x 20m, which was upscaled to the stand level by calculating the weighted average of each variable for each cell within each stand polygon (polygon shapes were defined during the last provincial round of the photo interpreted forest inventory and last updated in the year 2020). Each polygon was assigned a stand type based on its composition and age class structure (Bettinger et al. 2016), for its future connection with a yield table predicted by PICUS. On the land base, the balsam fir mixedwood (BFMX) stand type is the most abundant, representing 22% of the forest area in the inventory. White birch mixedwood (BIMX) and poplar hardwood (POHW) each represent 18% of the total working forest area, while intolerant softwood (INSW) covers 14%. Together, these four intolerant forest stand types cover almost three-quarters of the forest area, reflecting the dominance of individual shade-intolerant tree species in the Gagetown forest inventory (Figure 3.2). Moreover, all these stands comprise between 5-

20% red maple, which explains the elevated presence of the species across the initial landscape (Table 3.2). The remaining stand types — tolerant mixedwood (THMX), white pine softwood (WPSW), pure black spruce (BSPR), balsam fir, tolerant hardwood, spruce mixedwood (SPMX), mixed spruce softwood (MXSP), and birch hardwood (BIHW) — represent 28% of the working land base (Figure 3.2).

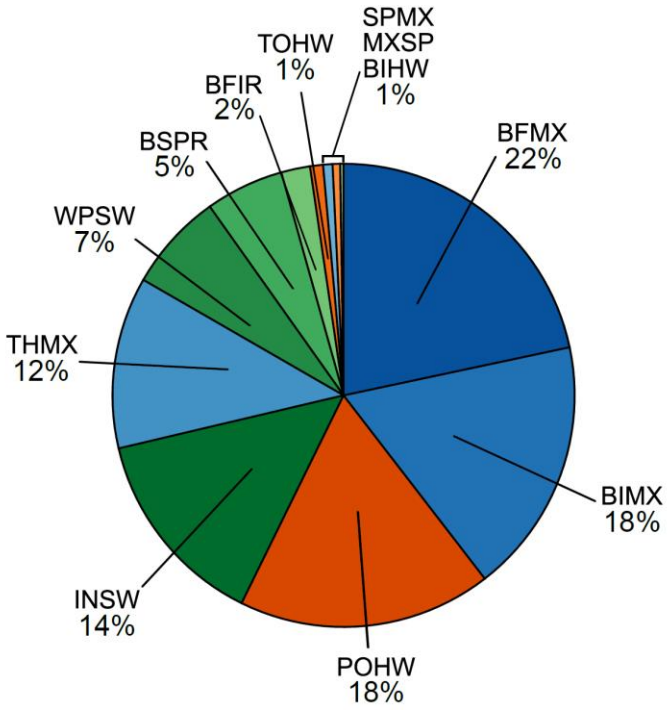


Figure 3.2. Stand type (Theme 1) repartition at the Gagetown study site. Note: orange = hardwood dominated stand types, green = softwood dominated stand types, and blue = mixedwood stand types, BFIR = balsam fir, BFMX = balsam fir mixedwood, BIHW = birch hardwood, BIMX = white birch mixedwood, BSPR = black spruce, INSW = intolerant softwood, MXSP = mixed spruce softwood, NCOM = non-commercial species, POHW = poplar hardwood, SPMX = spruce mixedwood, TOHW = tolerant hardwood, THMX = tolerant mixedwood, WPSW = white pine softwood; Percentage are relative to the working forest area.

Table 3.2. Composition of regeneration used to initiate each stand type simulation. Note: BFIR = balsam fir, BFMX = balsam fir mixedwood, BIHW = birch hardwood, BIMX = white birch mixedwood, BSPR = black spruce, INSW = intolerant softwood, MXSP = mixed spruce softwood, NCOM = non-commercial species, POHW = poplar hardwood, SPMX = spruce mixedwood, TOHW = tolerant hardwood, THMX = tolerant mixedwood, WPSW = white pine softwood; Percentages are relative to the working forest area.

Species	**BFIR**	**BFMX**	**BIHW**	**BIMX**	**BSPR**	**INSW**	**MXSP**	**POHW**	**SPMX**	**THMX**	**TOHW**	**WPSW**
Balsam fir	76%	60%	-	25%	35%	40%	15%	10%	15%	10%	-	20%
Red spruce	4%	-	-	-	-	-	35%	-	20%	20%	-	-
Black spruce	20%	-	-	-	65%	-	25%	-	15%	-	-	-
Red maple	-	20%	15%	15%	-	5%	-	15%	15%	-	15%	15%
White birch	-	20%	60%	40%	-	-	-	15%	15%	-	10%	-
Trembling aspen	-	-	15%	10%	-	10%	-	60%	-	-	-	-
Yellow birch	-	-	10%	-	-	-	-	-	-	25%	30%	-
Tamarack	-	-	-	-	-	30%	-	-	-	-	-	-
White spruce	-	-	-	5%	-	10%	25%	-	20%	-	-	15%
White pine	-	-	-	5%	-	5%	-	-	-	-	-	30%
Sugar maple	-	-	-	-	-	-	-	-	-	25%	45%	-
Eastern hemlock	-	-	-	-	-	-	-	-	-	20%	-	-
Red pine	-	-	-	-	-	-	-	-	-	-	-	20%

3.2.2 Process-based stand simulation model – PICUS

To simulate forest stand dynamics, we used the spatially explicit process-based model PICUS (version 1.5; Lexer and Hönninger 2001; Taylor et al. 2017). PICUS simulates the dynamics of individual trees on 10×10-meter patches of forest across stand areas, generally ranging from 100 to 1,000 patches corresponding to total stand areas of 1-10 ha. The model accounts for spatially explicit interactions among patches via a 3D light module and simulates seed dispersal explicitly, as well as the effects of climate and soil

properties on tree population dynamics (Lexer and Honninger, 2001; Taylor et al. 2017). A complete description of the model and its parameterization and validation for our study area can be found in Taylor et al. (2017).

3.2.2.1 PICUS initialization

Stand yield tables are used to forecast the development of stand attributes over time and are critical for supporting strategic forest management planning (Bettinger et al. 2016). We used PICUS to generate yield tables for each stand type. Simulations were initiated as 1-ha stands of young tree saplings (1.3-2 m tall) at a density of 5,000-10,000 stems·ha^{-1}. The species composition of saplings used to initiate each stand type simulation (only for age class 0-25, and transition period 2020-2050) was defined by the occurrence of each species within each major stand type found in our study area (Table 3.2). We then extracted stand conditions from each baseline yield tables of every stand type at 25, 50, and 75 years old to initiate the simulations for the three additional initial age class under climate change (25-50, 50-75, and 75+, see section 3.2.2.2).

PICUS requires estimates of stand soil conditions, including pH, available nitrogen (kg·ha^{-1}·year^{-1}), and water-holding capacity (i.e., field capacity, in mm) to initialize and simulate each stand. Because the forest study area has very limited soil records, all soil information to parameterize PICUS was derived from interpolated spatial soil data produced by Mansuy et al. (2014) and mean values for the entire forest were applied to all stand simulations.

PICUS uses monthly time-series climate data to simulate stand dynamics. Baseline climate data for 1981-2010 were obtained from high-resolution (1 km) interpolated climate

grids provided by Natural Resources Canada (McKenney et al. 2011). Future climate data were obtained from the Canadian Earth System Model version 2 (CanESM2) using data from the Climate Model Intercomparison Project Phase 5 (CMIP5) for two climate forcing scenarios known as Representative Concentration Pathways (RCP), namely RCP4.5 and RCP8.5. In the RCP4.5 scenario, climate forcing is assumed to stabilize at 4.5 $W \cdot m^{-2}$ after 2100 without an "overshoot" pathway. Conversely, in the RCP8.5 scenario, the forcing reaches 8.5 $W \cdot m^{-2}$ in 2100 and continues to increase for an unspecified period afterwards.

3.2.2.2 Design of PICUS simulations

To simulate the twelve stand types of the study area under three different climate scenarios (i.e., Baseline, RCP4.5, and RCP8.5), yield tables and transition rules first had to be modeled using the stand model PICUS (Figure 3.3). Because climate change affects temperature and precipitation regimes over time, yield tables and transition rules built to account for climate forcing scenarios must reflect the dynamic nature of climate change and be "time dependant" rather than "age dependent." This means that forest conditions occurring after the initialization period (i.e., the starting conditions of the simulation) cannot be used to describe conditions at any other future point in time directly. Instead, they must be dynamically updated based on the changing climate variables specific to each climate forcing scenario. Each time step in these simulations will reflect the evolving climate impacts on forest growth and development, ensuring that the model captures the progressive nature of climate change. However, it is important to note that all scenarios, whether climate forcing or not, must begin their simulation in Woodstock with the same

initial forest conditions; it is from this common starting point that different trajectories will emerge and be comparable between scenarios.

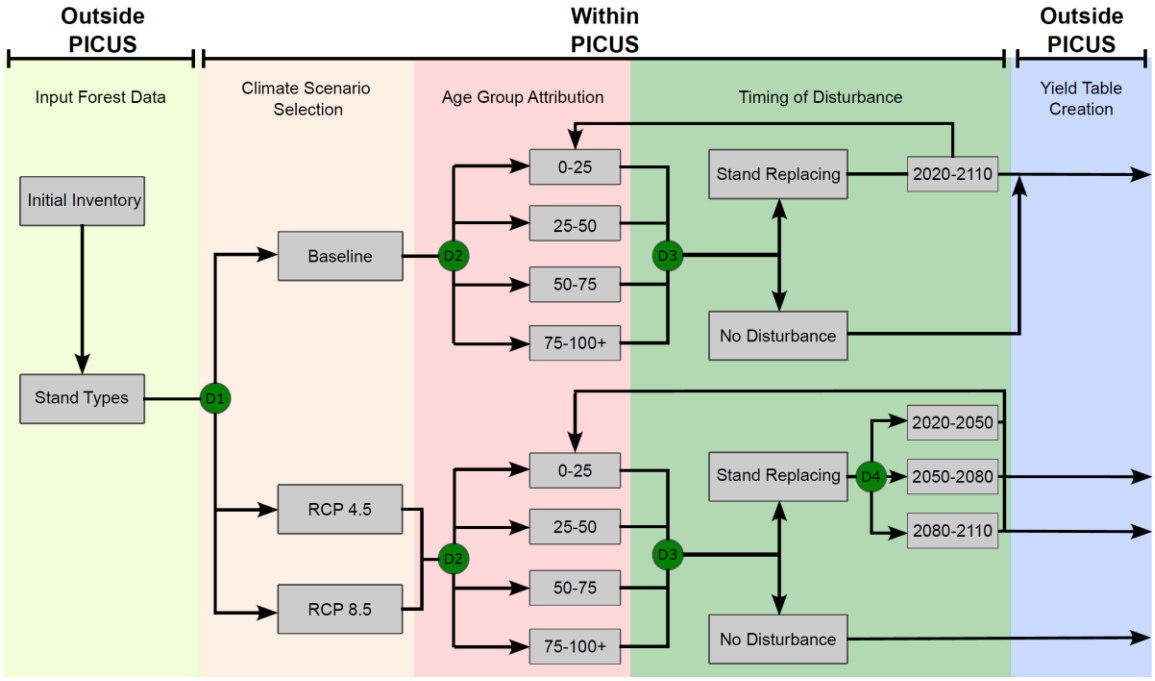


Figure 3.3. Simulation setup to model yield tables using the individual tree-based and process-based simulation model PICUS under three climate change scenarios. Note: D1-D4 represent decisions in the modelling simulation design that influence the generated yield tables.

Because the forest landscape comprises stands of different ages, and each stand will experience changes in climate over time differently depending on its age when the simulation is initialized, we cannot rely on the same age-based yield tables and transition rules for all stand age classes. Thus, we developed age class specific yield tables and transition rules to account for differential effects of climate change on stands of varying ages over time. Each forest polygon of the initial inventory was categorized into one of

four age class groups: 0-25, 25-50, 50-75, and 75+ (Figure 3.3; described in section 3.2.3.1). To capture a wide range of stand developmental conditions that would occur during the planning horizon, simulations based on initial forest conditions in yield tables were run for a 120 year planning horizon of 24 planning periods. These simulations were conducted for each of the four age groups across the twelve stand types and for each of the three climate scenarios (Baseline, RCP4.5, and RCP8.5), resulting in a total of 144 yield tables (Figure 3.3). The long simulation period allows us to understand how each age class and stand type would evolve under different climate conditions.

Two possible futures exist past the initialization time point in this case study: the first is that a stand is never harvested and continues its natural development, and the second is that clearcut harvesting occurs at some point (Figure 3.3). For Woodstock to comprehensively model the future of a stand that undergoes clearcut harvesting, growth and successional patterns generated from PICUS must be used to create yield tables and transition rules that reflect these differential stand responses. For the baseline climate scenario, yield tables and transition rules remain age-based, and there is no need to differentiate developmental responses due to climate change—that is, when a disturbance occurs under the baseline scenario, stand age is simply reset to age zero, and the same table from the 0-25 initialization age class group is used (Figure 3.3). Under the climate forcing scenarios, the timing of harvesting should influence the resulting stand development, given the gradual change in climate. To account for this effect, we developed different post-harvest yield tables and transition rules for three different climate periods: 2020-2050, 2050-2080, and 2080-2110. More specifically, stands disturbed during the 2020-2050 climate period are reset back to the 0-25 initial baseline age class yield tables and transition

rules, as climate sensitivity analysis conducted with PICUS showed no significant differences in growth and successional dynamics from climate change during this first part of the century. However, stands disturbed in mid to late parts of the century (i.e., the 2050-2080 and 2080-2110 climate periods) are reset to yield tables and transition rules for their respective climate periods, thus capturing the unique effect of climate change during those periods on stand dynamics. This method to incorporate climate change in transition rules integrated into Woodstock resulted in the creation of two new sets of yield tables describing these transition rules for regeneration dynamics for each of the twelve stand types under both climate forcing scenarios (RCP4.5 and RCP8.5). Consequently, a total of 48 new transition-based yield tables were developed.

3.2.2.3 PICUS simulation output variables

PICUS generates a wide variety of stand-level indicators, including individual tree recruitment, growth and mortality output data, changes in stand stem density, basal area, wood volume, and carbon stocks. Therefore, careful selection of indicators for inclusion in the PICUS-generated yield tables to input into Woodstock to characterize forest conditions is important. For this project, indicators such as merchantable volume by tree species ($m^3 \cdot ha^{-1}$), top height (m), and density ($stems \cdot ha^{-1}$) were included in the yield tables due to their direct relationship with wood supply and anticipated climate change effects (e.g., Honer et al. 1983; Álvarez-Miranda et al. 2018; Searls et al. 2021).

3.2.3 Strategic forest management planning model

The forest management planning model Woodstock Optimization Studio (Remsoft 2023) was used to assess the impacts of climate change on the forest planning unit.

Woodstock is widely utilized as a forest management planning model and decision support system around the world and can provide management planning solutions (i.e., management activity schedules) based on two decision support methods: binary search and linear programming optimization (Bettinger et al. 2016). Binary search involves repeatedly dividing the search interval in half to find the optimal solution based on selected actions and specified targets. Linear programming optimization (referred hereafter as "optimization") is a mathematical programming approach to finding the best possible solution, often by maximizing or minimizing a specific objective function under certain constraints. While optimization is usually the most popular technique used in natural resource management planning (Kaya et al. 2016), binary search was used in this study for its simplicity and its non-dependence on an objective function that could influence the results while still being able to test both yield tables and transition rules. The binary search was set up using only the clear-cutting action, with the target of harvesting approximately 1% of the working forest landscape each year, which equates to about 870 $ha \cdot year^{-1}$, targeting harvesting stands with the highest predicted volume decline first. We used the area control method because we mainly wanted to report the effect of climate change on the volume harvested. This harvest rate was chosen because it closely aligns with the average rates currently used in boreal-temperate forests (Nabuurs et al. 2007; Schroeder et al. 2011; Giasson et al. 2023).

3.2.3.1 Yield tables and transition rules assignment to the initial inventory

Three important forest variables—volume per species, top height, and density—were extracted from the 2018 forest inventory available at the study site to link each forest stand

in the inventory to the appropriate initial yield table for each stand type being modeled. These variables were selected as they were also generated by PICUS during the stand simulation process. To accurately represent initial forest conditions in the strategic model, two important selection criteria had to be considered: (1) match the correct stand type yield table to each inventory stand based on species composition, and (2) select the correct point on the age-based yield table for each stand type that corresponds closest in top height, volume, and density to the inventory stands. This procedure, described as inventory matching, relied exclusively on the baseline yield tables because climate-adapted yield tables are inherently time-dependent. Using them would require selecting a specific future year as a starting point, which would break the temporal sequence of projected climate impacts. This would compromise the internal consistency needed to model how forest growth evolves under progressively changing climatic conditions starting with current conditions.

In Woodstock, the land classification schemes are named "THEMES," akin to map layers in a geographic information system or stand attributes in a database. Four themes were employed for yield tables stratification. This classification guides Woodstock in selecting the suitable yield tables for each forest stand initially and following a transition (Table S3.1). The first theme characterizes stand types, in this case, twelve, reflecting the dominant species in the study area's forest cover. The second theme categorizes the initial stand condition into four age classes, considering stands that have undergone clear-cutting and are transitioning towards a "Future stand." The third theme links future regeneration following disturbance with an appropriate yield table based on the simulation period, allowing the model to account for the gradual climate change over the 100-year simulation

period. The fourth theme selects the appropriate set of yield tables based on the climate scenario being simulated.

3.2.3.2 Forest condition indicators

In Woodstock, outputs are programed to describe the state of the resource system in alignment with the user's management objectives. These landscape-level outputs serve as indicators to measure progress and provide insights into forest characteristics throughout the simulation. To discern differences among the three climate scenarios, we focused on three pivotal indicators. The first indicator examines the relative distribution of total merchantable growing volume across different species within the managed forest area, offering insights into species composition changes under various climate scenarios. The second indicator compares forest inventories in cubic meters, identifying differences in inventory levels resulting from changing climatic conditions. The third indicator evaluates financial performance through stumpage revenue and present value (PV) discounted at 4% (comparable to available investment alternative, i.e., government bonds). Revenue was calculated as the sum of stumpage values originating from the sale of four wood products: biomass, pulpwood, studwood, and sawlogs, with average prices of $2.00, $10.50, $21.00, and $35.00 per cubic meter, respectively (New Brunswick Reg 86-160 | Timber Regulation, 2024). Wood products were derived utilizing the merchantable volume ratio approach developed by Honer et al. (1983) and Kershaw et al. (2007). No costs were included in the net revenue calculation because the Government of Canada, acting as both decision maker and landowner, directly receives stumpage revenues from the sale of timber. Since harvesting and operational costs are borne by the buyers (e.g., contractors or

mills), these expenses are not relevant to the landowner's net revenue. For this reason, we refer to stumpage revenue hereafter.

3.3 Results

Our approach generated 16 yield tables for each stand type, including twelve yield tables for the four initial age classes across all three climate scenarios. To account for future regeneration following clear-cutting, four additional yield tables were developed to represent two future regeneration periods (2050-2080 and 2080-2110) under the two RCP scenarios. Considering that there are 12 stand types present at the study area, a total of 192 yield tables were produced.

3.3.1. Stand dynamics

The yield tables developed for all stand types revealed significant fluctuations in both merchantable volume and species composition across different climate scenarios and stand ages (Figure 3.4; see Figure S3.1-S3.3. for a complete list of yield tables used for initialization). Under the baseline climate scenario, overall volumes exhibited a non-linear increase with stand age, peaking at 200-300 $m^3 \cdot ha^{-1}$. However, under the RCP climate forcing scenarios, the peak was generally smaller, closer to 200 $m^3 \cdot ha^{-1}$, indicating a notable reduction in volume due to climate change. In general, volume reductions ranged from 10-15% for RCP4.5 to 20-25% for RCP8.5 (Figure 3.4).

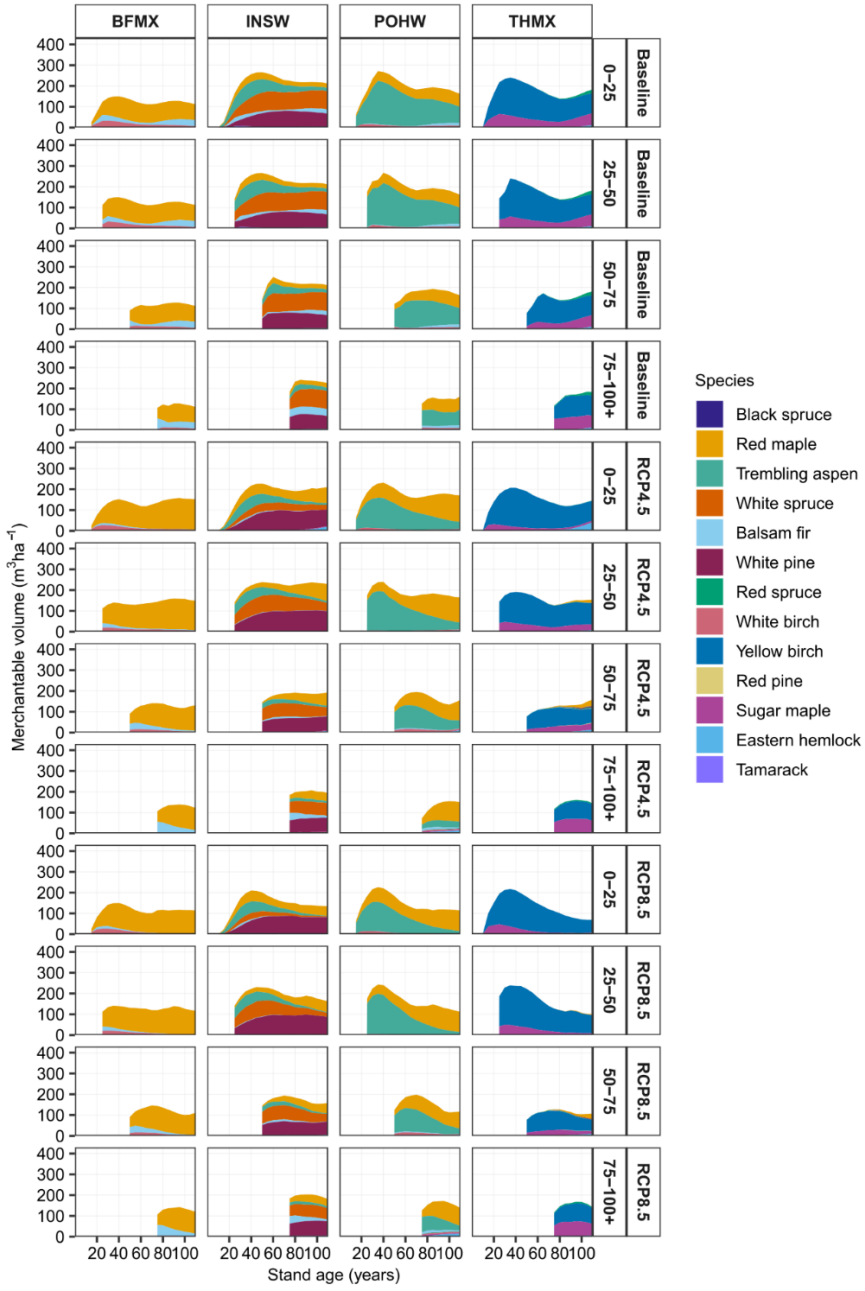


Figure 3.4. Volumetric yield tables generated from the stand model PICUS to initialize the landscape model Woodstock. The yield tables are presented for four stand types (BFMX = balsam fir mixedwood, INSW = intolerant softwood, POHW = poplar hardwood, THMX = tolerant mixedwood) across different initialization age groups (0-25, 25-50, 50-75, 75-100+) and climate scenarios (Baseline, RCP4.5, RCP8.5).

When investigating yield tables merchantable volume evolution, the spruce mixedwood stand type emerged as the most vulnerable to climate change, experiencing substantial reductions in volume under both climate forcing scenarios, with decreases of 50% and 75%, respectively, after 100 years of simulation (Figure S3.4). In contrast, the white pine softwood type demonstrated greater resilience, with limited volume reductions of only 10%. Across all stand types under both RCP scenarios, there was a notable increase in the abundance of red maple, suggesting a climate-driven shift in species composition over time (Figure 3.4). This shift in composition was particularly pronounced in stands of balsam fir mixedwood, birch hardwood, and poplar hardwood, where red maple comprised more than 75% of stand volume 80 years post-initialization. Yellow birch also emerged as potentially better adapted to projected climate changes, slightly outcompeting sugar maple and other tree species in the tolerant mixedwood and tolerant hardwood stand types. Conversely, trembling aspen, balsam fir, and spruces exhibited a continuous decline in abundance in each stand type over time compared to the baseline climate scenario (Figure 3.4). Notably, balsam fir completely disappeared from all yield tables beyond the 100-year simulation period.

Climate change also affected merchantable volume and species composition following clearcut harvesting (Figure 3.5; see Figure S3.4. for a complete list of transition rules). Post-harvest transitions occurring during the 2020-2050 period exhibited moderate shifts in species composition relative to the baseline, as cold-adapted species such as balsam fir and trembling aspen struggled to regenerate. Most stand types maintained their peak volume under RCP4.5 relative to the baseline scenario, while volume reductions under RCP8.5 reached 25% by 2050-2080 and 50% by 2080-2110. The tolerant

mixedwood type was among the lowest-performing stand types under RCP8.5, dropping to approximately 100 $m^3 \cdot ha^{-1}$ in the 2080-2110 period compared to 400 $m^3 \cdot ha^{-1}$ under the baseline scenario (Figure 3.5).

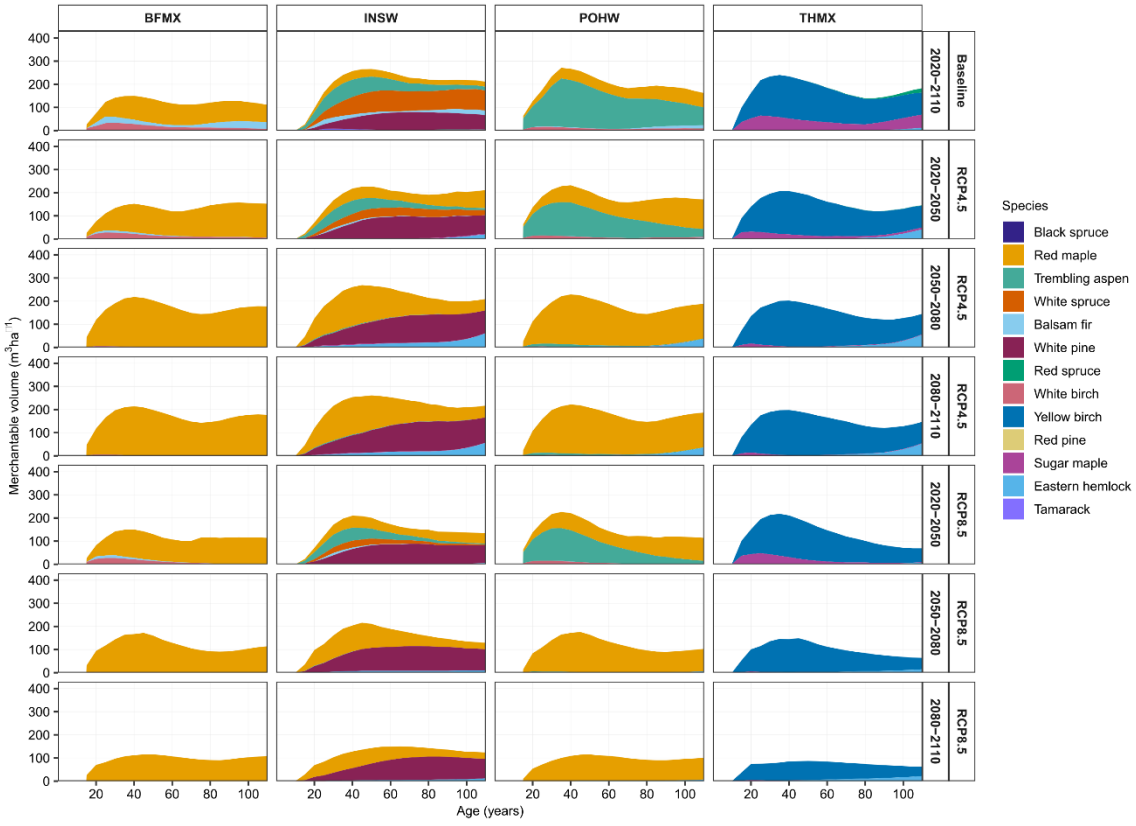


Figure 3.5. Transition rules resulting from PICUS simulations and integrated into the landscape model for four stand types, three transition periods, and three climate scenarios. Stand composition by tree species up to 110 years following harvest for the following subset of stand types: BFMX (balsam fir mixedwood), INSW (intolerant softwood), POHW (poplar hardwood), and THMX (tolerant mixedwood).

Species richness declined in most stands under RCP8.5, as cold-adapted species such as balsam fir, spruces, trembling aspen, and white birch failed to regenerate or survive

warming beyond a mean annual temperature increase of 4ºC, resulting in stands dominated by only one or two species after harvest in the latter half of the century under RCP8.5. The same trends were observed under RCP4.5; however, the decline in diversity only occurred during the 2080-2110 period. In intolerant softwood stands, red maple constituted up to 61% of stand volume 30 years after harvest under RCP8.5 by 2080-2110, compared to 33% under RCP4.5 for the same period (Figure 3.5B). Despite notable year-to-year variability (gray lines; Figure 3.6A) the climate forcing scenarios projected an average warming of 4-7°C by 2100 compared to the baseline (red loess function; Figure 3.6A). We observed increases in the relative abundance of less common species such as eastern hemlock and jack pine under RCP4.5 (Figure 3.5A and B), but their overall proportion of stand volume and composition remained marginal (<10%). Generally, most stand types across all climate-forcing scenarios converged towards dominance by red maple, white pine, or yellow birch, depending on their initial composition before harvesting, with the rate of conversion being highest under RCP8.5 (Figure 3.5B and Figure 3.6A-B).

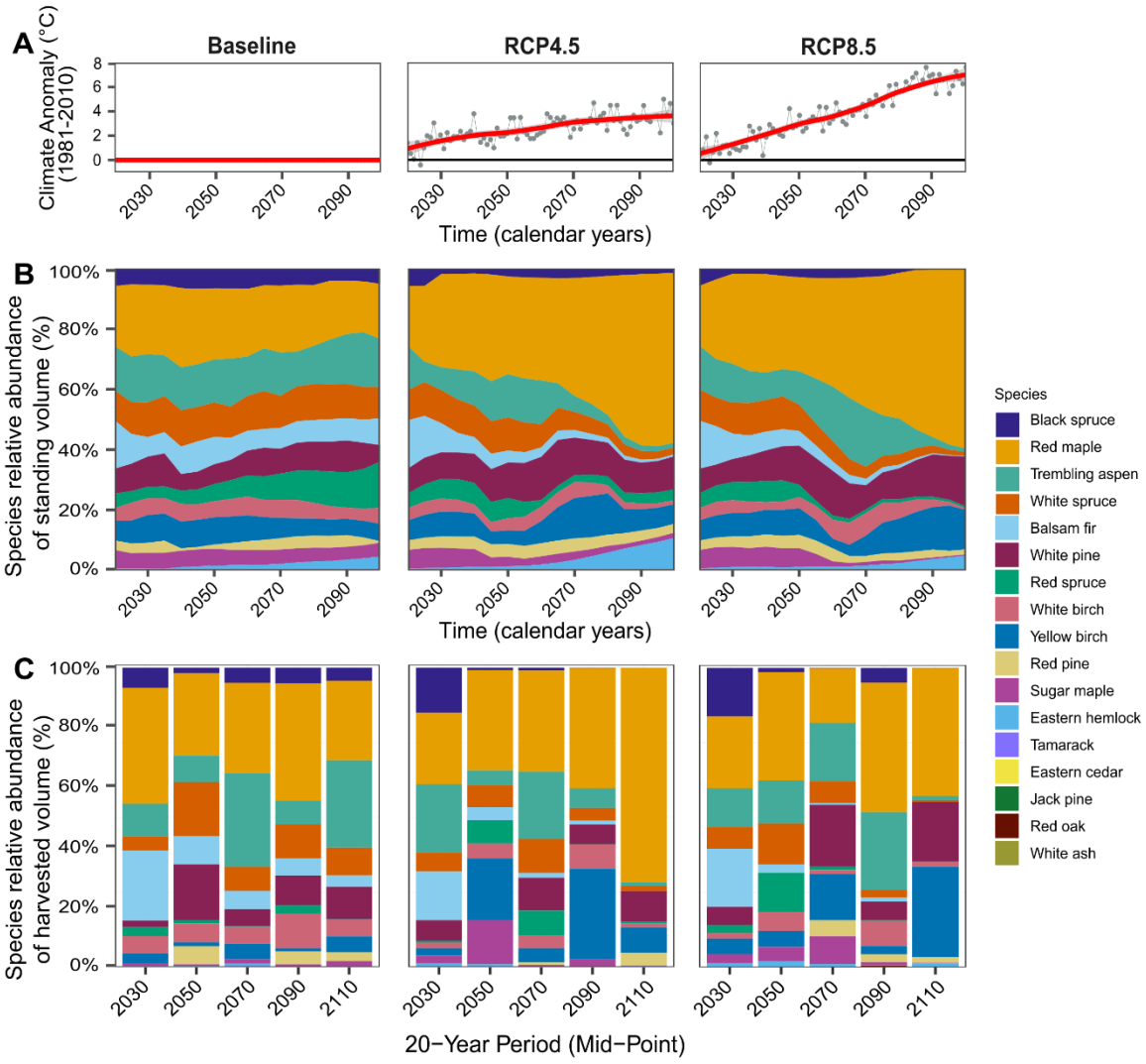


Figure 3.6. Forest evolution over the baseline, RCP4.5, and RCP8.5 climate scenarios. **A)** Climate anomaly in the study area with gray dots and lines representing the temperature anomaly reported for each year by the CanESM2. **B)** Tree species relative abundance of standing volume at the landscape level over time. **C)** Tree species relative abundance of harvested volume averaged over 20-year periods. Note: species in the legend are ordered according to their average baseline relative abundance of standing volume.

3.3.2. Forest landscape dynamics and management

3.3.2.1. Forest landscape composition and structure

Under the baseline climate scenario, species composition across the landscape remained relatively stable (Figure 3.6B). However, under RCP4.5, the relative abundance of red maple increased from approximately 20% of the landscape to 50% by the year 2090, while its abundance never exceeded 25% under the baseline scenario. Yellow birch and eastern hemlock also displayed increases from 8% to 15% and from less than 1% to over 10% by 2090 under RCP4.5, respectively, changes not observed under the baseline scenario (Figure 3.6B).

Under the more severe RCP8.5 climate forcing scenario, red maple increased even more dramatically, occupying over 60% of the forest landscape by 2100. By the end of the simulation, yellow birch, and white pine each comprised about 12% of the forest inventory. Together, red maple, yellow birch, and white pine accounted for approximately 85% of the total merchantable volume by 2100, compared to only 30% in the baseline scenario (Figure 3.6B). Conversely, trembling aspen decreased in relative abundance from 15% to around 5% under RCP4.5. The notable gain of red maple, yellow birch, and white pine resulted in a substantial decline of other species such as balsam fir, spruces, white birch, sugar maple, and red pine, which were only marginally present (<6%) on the landscape by the end of the century.

3.3.2.2. Forest harvesting and operations

Under the baseline scenario, the proportion of tree species harvested remained relatively stable, with red maple, trembling aspen, and white spruce being predominant

(Figure 3.6C). Under RCP4.5, there was an increase in the variation of wood harvested, particularly towards the end of the century. By 2100, the harvested volume of red maple increased to over 45% of the total annual cut, up from an average of 30% under the baseline scenario. The proportion of harvested yellow birch and sugar maple also rose under RCP4.5, especially during the last third of the simulation, largely due to substantial growth reductions under climate warming exceeding 3ºC, which placed their stand types earlier in the harvest queue (Figure 3.6C). At its peak, yellow birch accounted for 60% of the total volume harvested, up from 10% under the baseline scenario.

The RCP8.5 scenario displayed the greatest variability in harvest volume and species mix, with red maple harvests increasing to approximately 40% consistently throughout the simulation. Yellow birch was intensely harvested during the 2040-2060 and 2080-2100 periods, accounting for 15% and 30% of the total volume harvested, respectively, with some years reaching 70%. A similar trend was observed under RCP4.5. Under both climate forcing scenarios, stands containing tree species vulnerable to climate warming, such as balsam fir, spruces, and trembling aspen, tended to be harvested earlier in the simulation.

Under the baseline scenario, the proportion of hardwood and softwood harvested remained relatively stable at 62% and 38%, respectively (Figure 3.7A). Under RCP4.5, the average hardwood harvest increased to 75% over the simulation period. Under RCP8.5, hardwoods accounted for 69% of the harvested volume, with softwoods at 31%. Both climate scenarios show an increasing reliance on hardwood harvests as temperatures rise. Red maple and yellow birch were among the most harvested hardwood species (Figure 3.7A).

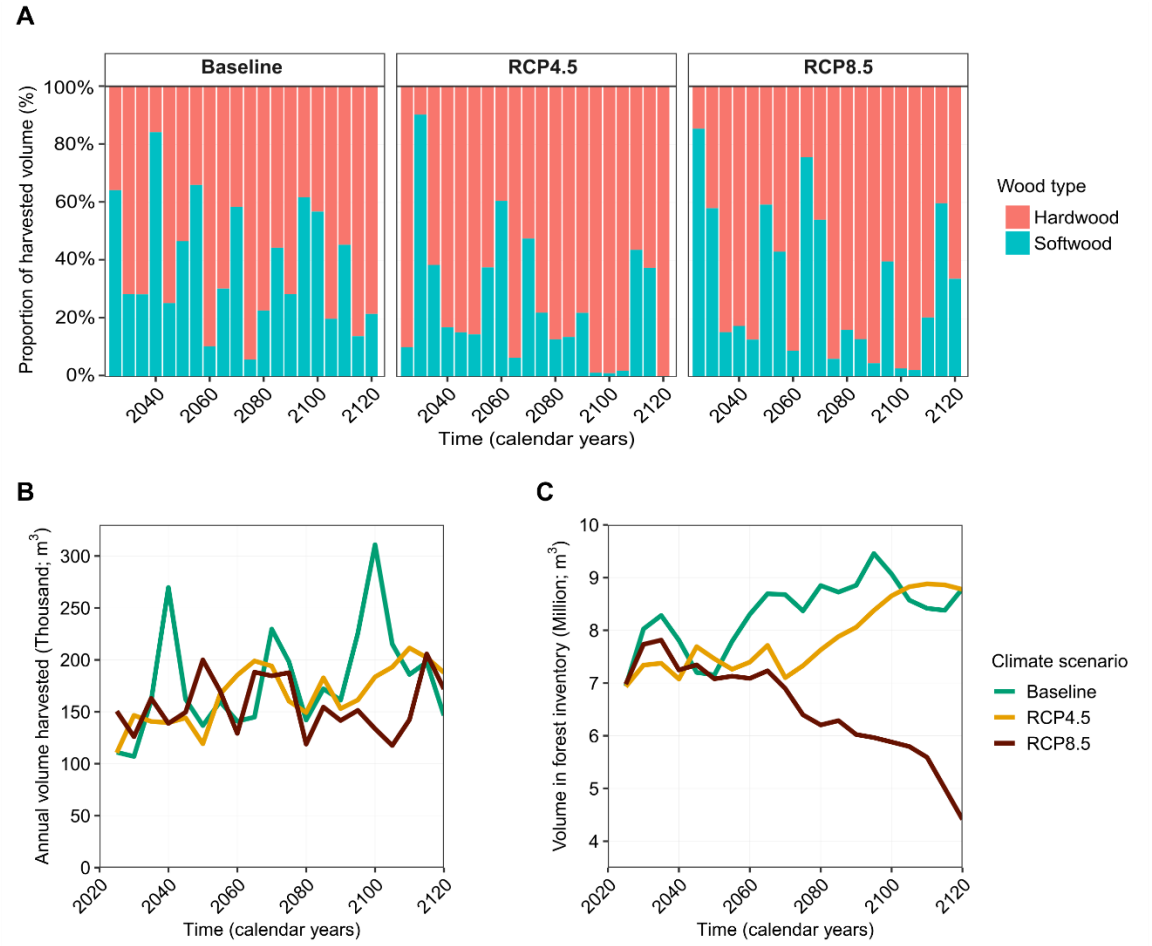


Figure 3.7. Harvested wood type proportions and forest inventory under the baseline, RCP4.5, and RCP8.5 climate scenarios. **A)** Proportion of harvested volume by wood type (hardwood and softwood). **B)** Annual volume of timber harvested across the simulated horizon. **C)** Volume available in forest inventory over the simulations.

Under the baseline scenario, the total annual volume of timber harvested fluctuated between 150 000 and 300 000 m^3 per year but declined to 110 000–200 000 m^3 per year under the two climate forcing scenarios (Figure 3.7B). Harvested volume varied across planning periods because the binary search setup controlled the harvested area, not the

volume. As a result, the same area was harvested each year, but volume differed due to variations in stand productivity across the landscape. On average, the volume harvested per hectare under the baseline scenario (300 $m^3 \cdot ha^{-1}$) was higher than in the two climate forcing scenarios, which averaged 230 $m^3 \cdot ha^{-1}$, especially during the peak harvest years of 2040, 2070, and 2100. Under RCP8.5, the annual volume harvested showed a clear decline between 2070 and 2110 (Figure 3.7B). Despite this decline in harvest, forest inventory under RCP8.5 fell well below both the baseline and RCP4.5 levels (Figure 3.7C).

The baseline scenario showed a steady increase in forest inventory volume over time, peaking at 9.5 Mm^3 across the landscape by 2070 and roughly maintaining that level until 2120, with an average gain of 20 000 $m^3 \cdot year^{-1}$ over the course of the 100-year simulation. In contrast, under the RCP4.5 scenario, forest inventory volume increased at a slower pace during the first 40 years, followed by a significant growth surge around 2070 (Figure 3.7C). After this point, the inventory gained approximately 40 000 $m^3 \cdot year^{-1}$ for the remaining 50 years of the simulation, ultimately resulting in a final inventory volume similar to the baseline scenario but with a different species composition. The RCP8.5 scenario, however, presented a more concerning trend. The forest inventory volume peaked at around 7.8 Mm^3 by 2030 but then continuously declined by about 25 000 $m^3 \cdot year^{-1}$, reaching only 4.5 Mm^3 by 2120, 50% lower than the volumes observed in the baseline and RCP4.5 scenarios (Figure 3.7C). The decline was particularly pronounced during the latter half of the simulation, with a decrease rate of nearly 40 000 $m^3 \cdot year^{-1}$. In this scenario, harvesting exceeded total forest growth, potentially leading to wood supply shortages in the future.

3.3.2.3. Economic impacts

The financial implications of climate change were measured by the changes in the PV of the forest, calculated as the cumulative sum of stumpage revenue, discounted at a rate of 4%. Under the baseline scenario, the PV reached $98 million, while the two climate forcing scenarios achieved approximately $90 million. Of particular concern is that both RCP scenarios lagged the baseline scenario in PV after the year 2040, demonstrating the immediate and growing effect of climate change on the profitability of the forest on stumpage revenue for the landowner (Figure 3.8). In fact, more volume was harvested under the baseline scenario during the first 30 years than in any other scenario, resulting in higher stumpage revenue and PV (Figure 3.8). The variability in annual harvested volumes and the resulting financial impacts were partly due to the reduced merchantable volume available under warming scenarios. Notably, more pulpwood was harvested during the latter half of the simulation under the climate forcing scenarios, whereas higher value products like studwood and sawlogs dominated the harvest in the baseline scenario.

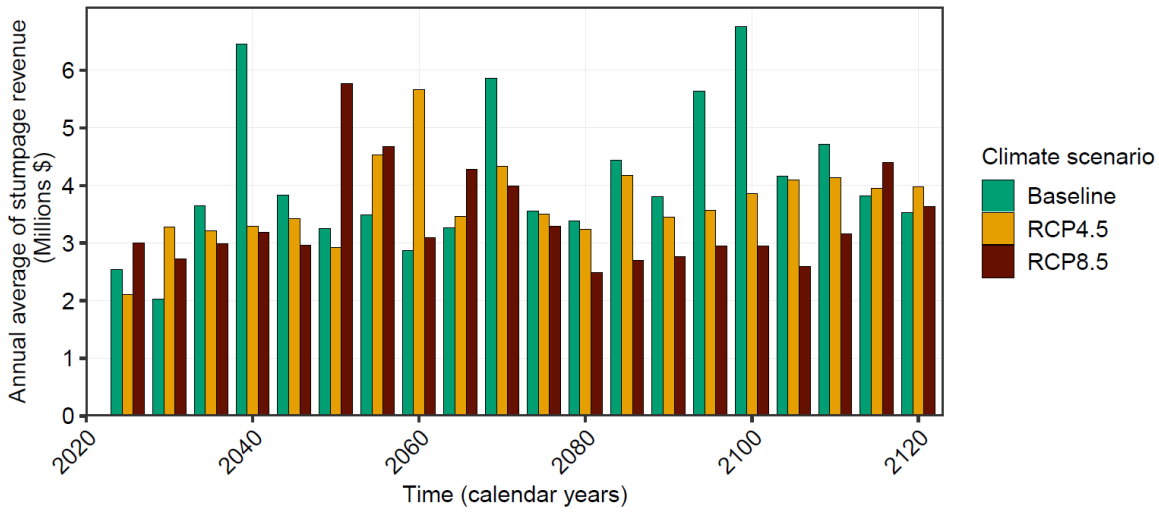


Figure 3.8. Annual average of stumpage revenue from forest management under the baseline, RCP4.5, and RCP8.5 climate scenarios for the simulated horizon.

3.4 Discussion

3.4.1. Application of dynamic yield tables and transitions

Climate-sensitive yield tables and transition rules, developed using the stand-level model PICUS, were successfully integrated into the strategic-level forest management planning model, Woodstock. Climate effects simulated at the stand level by PICUS were consistent with findings from other climate-related modeling studies (Ashraf et al. 2015; Thom et al. 2017; Morin et al. 2018; Searls et al. 2021), supporting their application in this study. Using Woodstock, we were able to user climate sensitive yield tables and transition rules to consider multiple climate forcing scenarios over the planning horizon

This approach differed from previous studies that relied on stand-level growth modifiers to simulate the effects of climate change on the forest landscape (e.g., O'Neill and Nigh 2011; Pukkala 2017; Mathys et al. 2018; Searls et al. 2021). Those studies

adjusted existing yield tables rather than developing new yield tables and transition rules that directly integrated the effects of climate change over time. Our method, utilized projected climate data to influence stand developmental processes in the process-based model PICUS, resulting in yield tables that were more ecologically realistic compared to the simpler scalar multiplication approach (Cuddington et al. 2013; Metsaranta et al. 2024). The primary advantage of this approach was the consideration of species-specific environmental responses to climate change, enabling more realistic predictions of forest dynamics under climate forcing scenarios (Achim et al. 2022; Metsaranta et al. 2024).

3.4.2. Effect of climate change on forest composition and yield

Landscape-level simulations under warming revealed a significant shift in forest composition, with red maple, white pine, and yellow birch emerging as dominant species after 100 years of simulation. This transition from boreal to temperate species was consistent with findings from other studies (e.g., Boulanger et al. 2017; Taylor et al. 2017; Brecka et al. 2020), who also observed significant reductions in species diversity and shifts in species dominance under the RCP8.5 climate forcing scenario. Similar to these studies, we identified spruce species and balsam fir as the most vulnerable to warming and noted an increased dominance of red maple and pines. However, of particularly note was the large increase in extent of red maple dominance beyond the year 2060, where it constituted approximately 60% of the available landscape volume under RCP8.5. This was a significantly higher prediction than reported in similar landscape modeling studies in the region (Ashraf et al. 2015; Boulanger et al. 2017). Under RCP4.5, growth gains in eastern

hemlock and white birch helped offset the reduction in growth of other species on the landscape. (D'Orangeville et al. 2016, 2018; Reich et al. 2022).

Moreover, the increased dominance of a few tree species, such as red maple, white pine, and yellow birch, significantly altered forest ecosystem services beyond timber production. Forest managers often prioritize non-timber objectives, such as maintaining wildlife habitats and protecting biodiversity, that rely on specific available landscape conditions. By setting targets for annual harvesting and silvicultural practices these conditions can ether be reached or created by forest management. However, climate change and the resulting shifts in species composition could disrupt these efforts making some landscape conditions impossible to reach. For instance, the increasing prevalence of these species may affect carbon sequestration rates and reduce habitat availability for wildlife, particularly in old-growth evergreen forests that rely on a diverse mix of species. Studies by McKenney et al. (2011) and Reich et al. (2022) have suggested that these compositional changes can have cascading effects on forest health and resilience, especially when tree species that were previously minor components become dominant.

3.4.3. Effect of climate change on wood supply and economic implications

Maintaining the scheduled harvesting regime under the projected climate forcing scenarios led to a wood supply shortage by the end of our planning horizon, a situation not detected under the baseline scenario. This finding indicates that current management plans that do not consider the effects of climate change are likely unsustainable if horizons longer than 100 years were to be considered. These results corroborate previous studies that analyzed aboveground biomass under different climate scenarios and predicted severe

reductions in wood supply under the RCP8.5 scenario (e.g., Boulanger et al. 2017; McMonagle et al. 2024). Moreover, studies assessing natural disturbance impacts on wood supply under climate change consistently indicate that sustainable harvest levels need to be reduced by 25-75% compared to current levels, due to projected growth declines and altered disturbance dynamics. (e.g., Armstrong 2004; Gauthier et al. 2015; Daniel et al. 2017).

The reduction in harvested volume across both climate forcing scenarios relative to the baseline scenario highlighted the significant, negative effects climate change will have on the economic feasibility of future forestry operations, supporting other recent studies that modeled the effects of climate change on forestry economics (e.g., Lantz et al. 2022; McMonagle et al. 2024). Indeed, our results show that RCP8.5 could lead to lower stumpage revenue and present value returns, particularly in the final 50 years of the simulation. Furthermore, the observed financial instability was due to the reduced merchantable volume and lower overall product quality under warming scenarios. Recent studies highlight that climate change could lead to increased volatility in forest yields, affecting economic stability (e.g., Ashraf et al. 2015; Taylor et al. 2017; Wang et al. 2023). Our findings suggest that strategic adaptation measures might be necessary to mitigate these financial risks. Shorter rotations reduce the duration of environmental stress for each stand, capturing potential mortality (e.g., Jönsson et al. 2015; Schelhaas et al. 2015), while species diversity enhances resilience and reduces climate related risks (Messier et al. 2019; Chen et al. 2023).

3.4.4. Limitations

There are some limitations of our approach that should be acknowledged. Future models should account for natural disturbances, as their severity and frequency are projected to change under warmer climates (e.g., Daniel et al. 2017; Taylor et al. 2020b; Brecka et al. 2020). The interaction between increasing disturbances and the warming effects on tree demographics may lead to more profound modifications to some stand types than either factor alone.

Only one anthropogenic disturbance, clear-cutting, was simulated in the landscape-level analysis, yet other research has indicated that harvest intensity, pattern, and frequency could impact forest succession and composition, potentially altering the effects of climate change on the landscape (e.g., Nagel et al. 2017; Taylor et al. 2020a; Moreau et al. 2022). Further research is needed to determine the potential impact of implementing dynamic climate-sensitive partial harvest yield tables and transition rules.

Additionally, our study did not account for uncertainties but rather modeled three distinct climate scenario certainties. However, important sources of uncertainty such as climate-driven shifts in species ranges and migration rates (Wang et al. 2018; Brice et al. 2019; Prasad et al. 2020) or site-specific factors like soil moisture and fertility (Anderegg et al. 2015; Boulanger et al. 2021) could significantly influence the development of yield tables and transition rules.

Moreover, significant uncertainties remain in stand-level models regarding tree species regeneration capacities under future climates, which could escalate further down the planning horizon (Boucher et al. 2020; Boulanger et al. 2021).

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Supplementary material

This supplementary material includes:

Table S3.1.

Figure S3.1. to Figure S3.4.

Table S3.1. The characterization theme used to stratify different growing conditions in forest stand in Woodstock.

Theme 1 **Forest unit names**	**Theme 2** **Initial age group**	**Theme 3** **Climate period**	**Theme 4** **Climate scenario**
Balsam fir (BFIR)	[0 to 25) years old	[2020 to 2050)	RCP4.5
Balsam fir mixedwood (BFMX)	[25 to 50) years old	[2050 to 2080)	RCP8.5
Birch hardwood (BIHW)	[50 to 75) years old	[2080 to ∞]	Baseline
White birch mixedwood (BIMX)	[75 to ∞] years old		
Black spruce (BSPR)	Future stand		
Intolerant softwood (INSW)			
Mixed spruce softwood (MXSP)			
Poplar hardwood (POHW)			
Spruce mixedwood (SPMX)			
Tolerant hardwood (TOHW)			
Tolerant mixedwood (THMX)			
White pine (WPSW)			

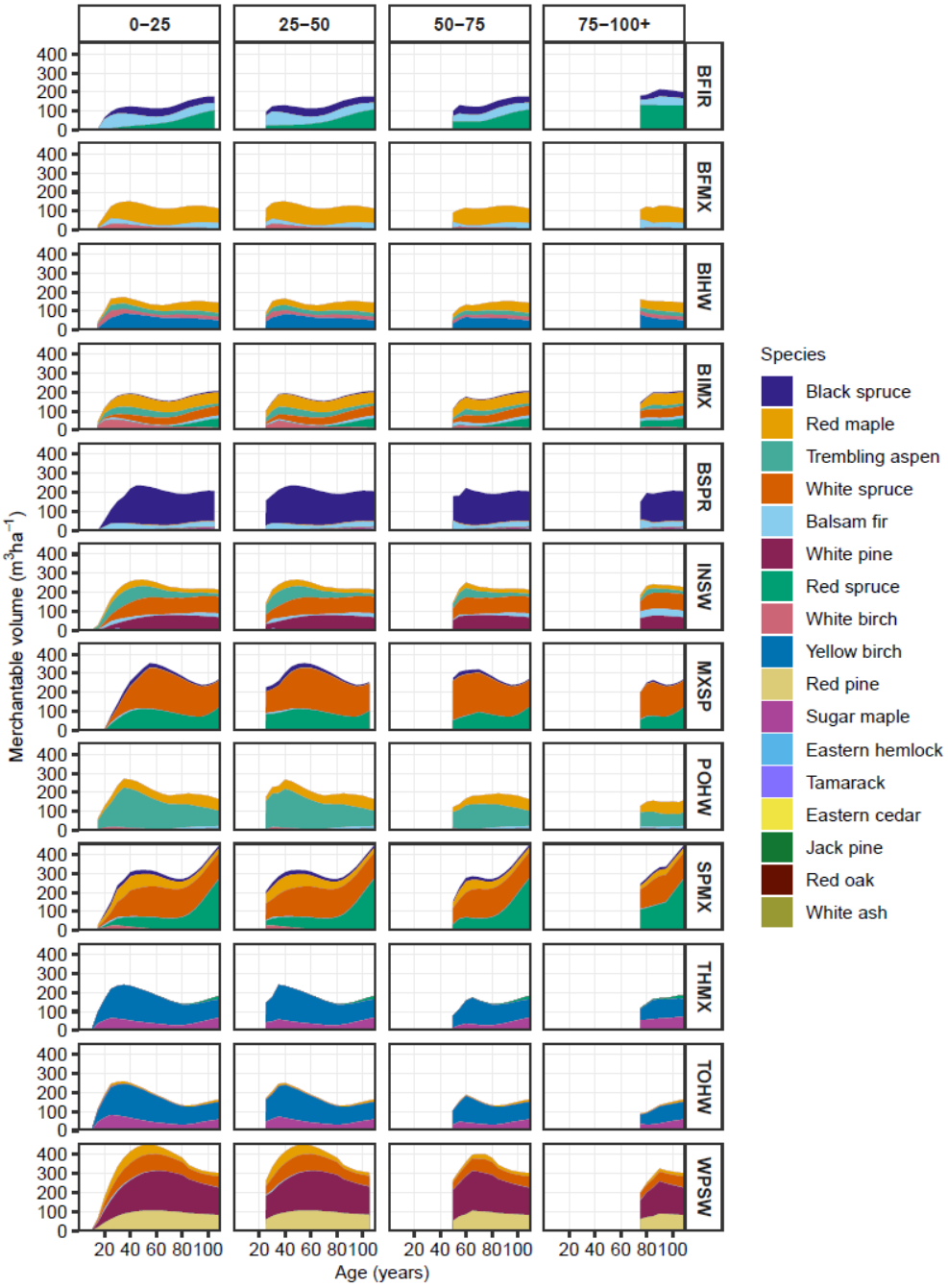


Figure S3.1. Baseline climate scenario volumetric yield tables generated from the stand model PICUS to initialize the landscape model Woodstock. The yield tables are presented for all stand types across different initialization age groups (0-25, 25-50, 50-75, 75-100+). Data is presented for the first 110 years.

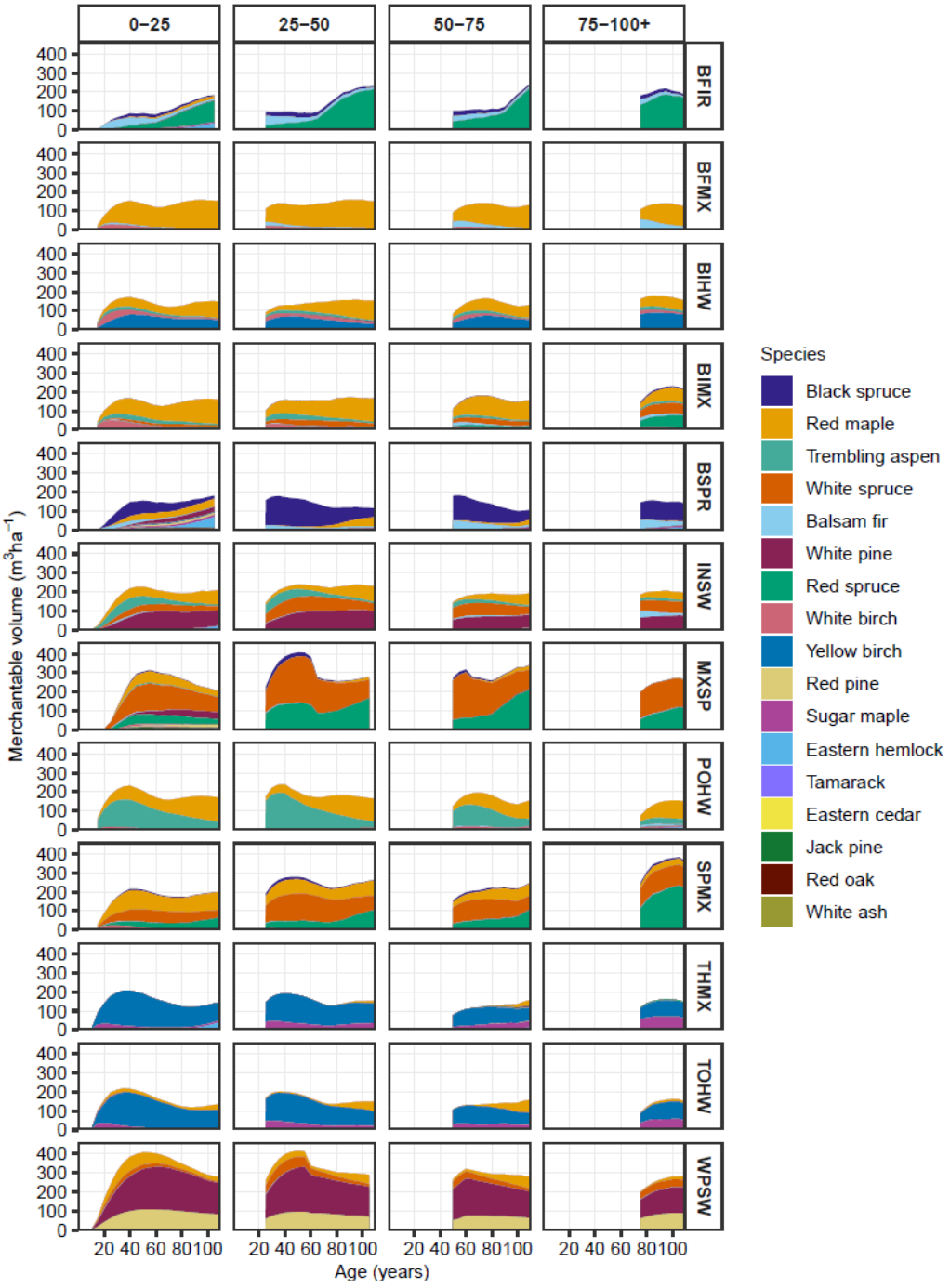


Figure S3.2. RCP4.5 climate scenario volumetric yield tables generated from the stand model PICUS to initialize the landscape model Woodstock. The yield tables are presented for all stand types across different initialization age groups (0-25, 25-50, 50-75, 75-100+). Data is presented for the first 110 years.

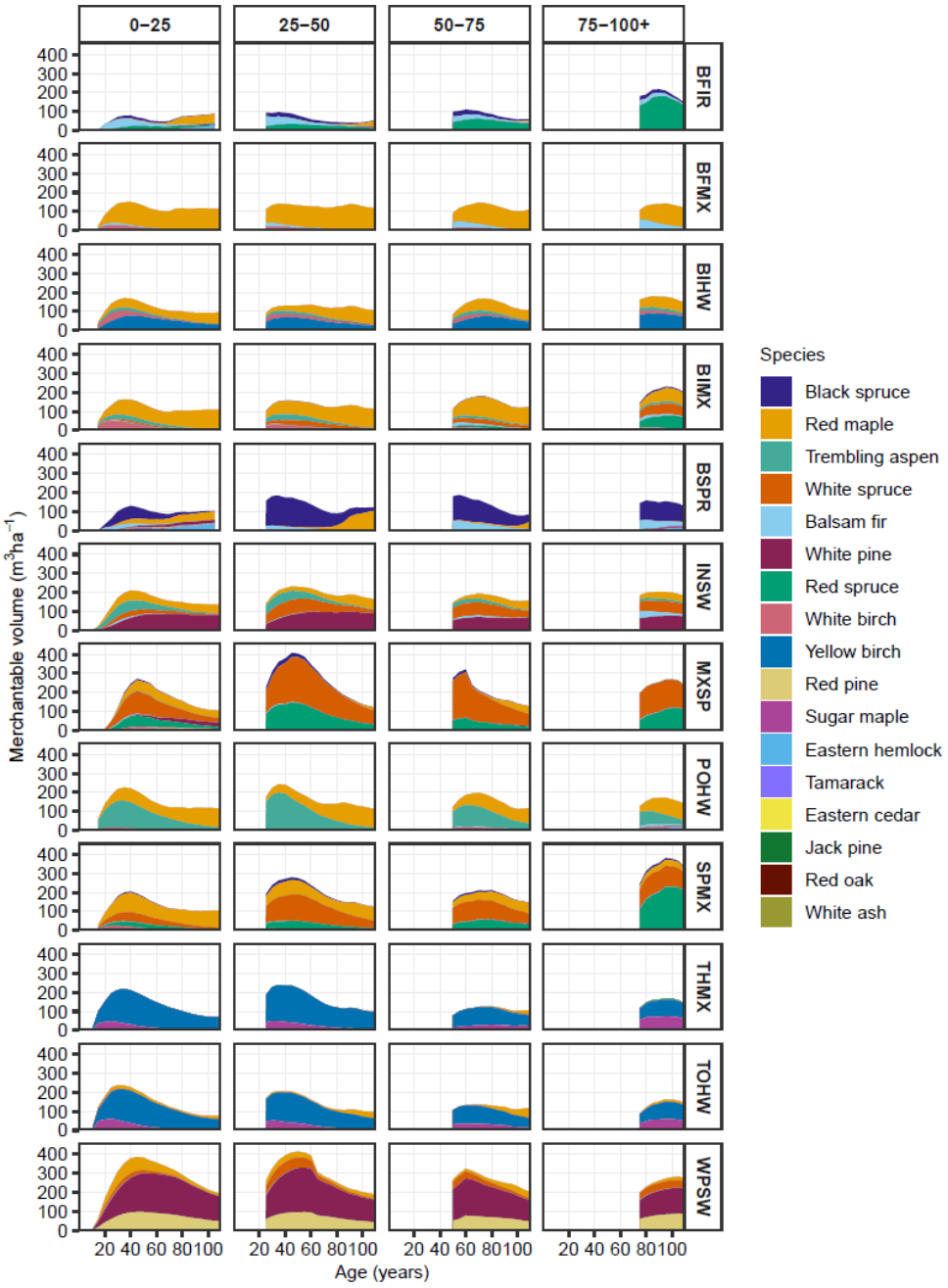


Figure S3.3. RCP8.5 climate scenario volumetric yield tables generated from the stand model PICUS to initialize the landscape model Woodstock. The yield tables are presented for all stand types across different initialization age groups (0-25, 25-50, 50-75, 75-100+). Data is presented for the first 110 years.

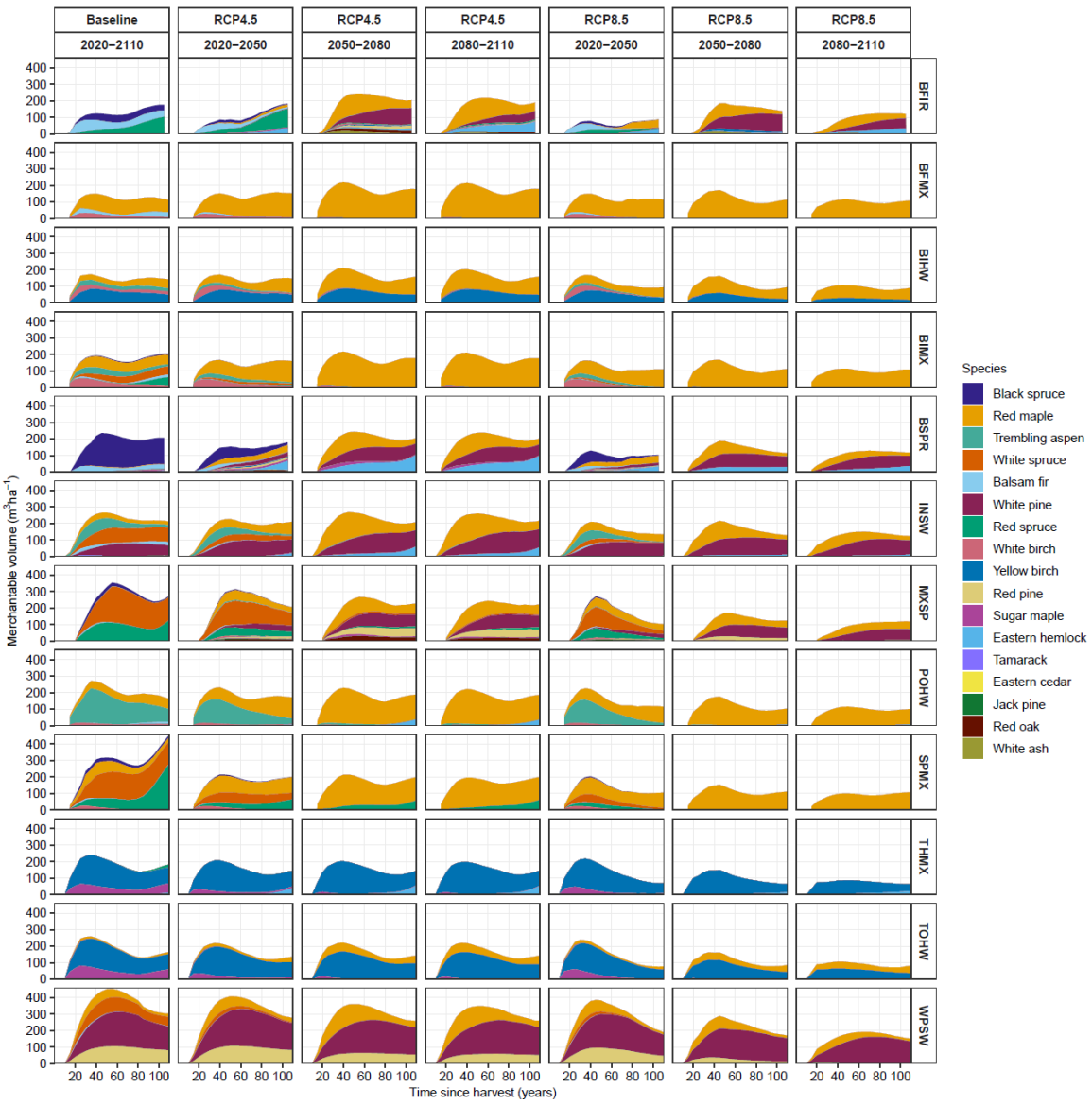


Figure S3.4. Transition rules (presented as yield tables following harvest) resulting from PICUS simulations and integrated into the landscape model for all stand types, transition periods, and climate scenarios. Data is presented for the first 110 years.

Chapter 4. Optimized scheduling of partial-cutting mitigates climate change impacts on wood supply and economic outcomes in the Acadian forest

Abstract

By affecting wood supply, climate change will force changes on forest planning, particularly through its impact on growth rates and the timing of interventions. This study uses an optimization modeling approach that integrates climate-sensitive yield tables and transition rules to assess wood supply. In southern New Brunswick, Canada, we paired PICUS, a process-based stand simulation model, with Woodstock, an optimization platform, to compare forest management under baseline and future climates (RCP4.5 and RCP8.5) from the IPCC Fifth Assessment Report. The objective function maximized stumpage revenue from timber sales, allowing clear-cut, low-retention (40% removal), and high-retention (10% removal) silvicultural treatments. We examined the changes in silviculture interventions, inventories, economics, and environmental outputs across the scenarios. Under warming, high-retention and clear-cut harvests were increasingly used to maximize stumpage revenue, a shift that was absent under baseline conditions. Under RCP8.5, areas under high- and low-retention harvests rose by factors of 1.2 and 2.3, respectively. These shifts were accompanied by a 4–9% decline in operable wood volume, a 6–10% drop in harvested volume, a 16–23% rise in temperate deciduous composition relative to cold-adapted conifers, and a 12–16% reduction in stumpage revenue under warming compared to the baseline. The optimizer shifted part of the silviculture toward retention harvest when climate sensitive yield tables were introduced but maintained a high

proportion of clearcutting highlighting that a diverse silvicultural toolbox, has the potential of mitigating the negative climate-change impacts on wood supply.

Keywords: Climate change, intervention schedule, landscape planning, sustainability, adaptation.

4.1. Introduction

Wood fibre supply is closely tied to forest size, stand dynamics, and the timing of silvicultural interventions, all of which are increasingly affected by climate change (Bettinger et al. 2016; Albert et al. 2023). Climate models project temperature increases of 4-7˚C across the Acadian forest of eastern Canada by the end of this century (Evans and Brown 2017), resulting in major shifts in stand growth, regeneration, and mortality (Albert et al. 2023). These landscape changes will impact forest management, as responses to silvicultural interventions and disturbances will no longer align with historical patterns (Albert et al. 2025).

Traditional forest landscape management planning models have largely relied on historical stand growth patterns to predict wood fibre supply (Yousefpour et al. 2012; Fettig et al. 2013). However, these empirical models may no longer hold under rapidly changing climatic conditions because of climate-driven shifts in stand dynamics (Taylor et al. 2017; Metsaranta et al. 2024), resulting in inaccurate predictions of growth rates and composition of regeneration (McDowell et al. 2020; Achim et al. 2022). Despite growing acknowledgement of this issue (Metsaranta et al. 2024), few studies have provided quantitative assessments of climate change effects on forest planning, particularly in the context of scheduling and regulating silvicultural interventions (e.g., Yousefpour et al. 2012; O'Hara and Ramage 2013).

While numerous studies have explored the broader impacts of climate change on forest ecosystems, including shifts in tree species distributions, growth rates, and regeneration dynamics (D'Orangeville et al. 2016; Wang et al. 2023), few connect these insights with forest management planning (Seidl et al. 2014; Albert et al. 2023, 2025). To

date, most jurisdictions still rely on historic, empirical stand models in their forest management planning, making critical decisions that have long-term implications with limited consideration of climate change impacts on future wood supply and other goods and services (Yousefpour et al. 2012; Metsaranta et al. 2024). Climate-sensitive process-based stand models are available to predict the effects of such changes on stand dynamics, even following various silvicultural interventions (Taylor et al. 2020a; Willis et al. 2023). For instance, process-based models have been used to evaluate the impacts of silvicultural strategies such as partial-cutting and clear-cutting approaches under warmer climates (Montoro Girona et al. 2018; Simard et al. 2021; Montwé et al. 2022).

Few studies have scaled their stand level findings to the forest landscape level to assess the combined effects of climate change on forest management at that broader spatial scale. While broad regional studies, such as those by Brecka et al. (2020) and Mina et al. (2022) have assessed the impacts of human interventions and natural disturbances on forested landscapes under changing climatic conditions, they primarily focus on large-scale trends rather than the finer-scale interactions between climate change and silvicultural practices at the stand and planning-unit level. Other research embracing adaptive silviculture for climate change, such as Nagel et al. (2017) and Gustafson et al. (2020), is limited to the stand level, developing new treatment types tailored to specific tree species assemblages. While valuable, these approaches have little broader applicability. Although silvicultural interventions play a critical role in shaping landscape responses to climate change, no studies have directly examined the use of conventional silvicultural practices to mitigate climate change effects on forested landscapes through linear programming optimization of their scheduling.

Silvicultural interventions generally fall into two categories: clear-cutting, which removes all merchantable trees, and partial-cutting, which retains a specific proportion (Bettinger et al. 2016). Clear-cutting remains the predominant silvicultural intervention in Canada because it reliably meets operational and economical objectives (Puettmann et al. 2015; Boucher et al. 2021). This method, defined by the complete removal of trees in a given area, favors fast-growing, shade-intolerant species such as red maple, white birch, white pine, and poplars under many site conditions, and when followed by reforestation, can generate vigorous, young stands with promising carbon sequestration potential and enhanced pest control (Taylor et al. 2020a; Elliott et al. 2020). Nevertheless, clear-cutting also removes protective canopy, thereby increasing temperature variability, water stress, and risks related to soil erosion and habitat fragmentation (Davis et al. 2019). Partial-cutting, is a strategy that can moderate microclimatic extremes, but primarily under conditions of drought or heat stress (Montwé et al. 2022). In these specific contexts, selecting tree species less adapted to climate change for removal and retaining a residual canopy cover may dampen temperature extremes and reduce water deficits, improving regeneration quality and survivability (Davis et al. 2019). Partial-cutting is also known to mitigate the effects of natural disturbances such as wildfires, drought, and insect outbreaks when realised at the appropriate timing in stand development (Ashton and Kelty 2018; Lafond et al. 2024). Yet, on average, clear-cut systems tend to be more productive, and the growth and regeneration benefits of partial-cutting remain highly context-dependent, influenced by species-assemblage specific responses and local environmental conditions (Maleki et al. 2021). There are also constraints to partial-cutting application in some regions like the boreal forest due to elevated mortality, growth stagnation, and problems

with desirable species recruitment detected post-harvest (Bose et al. 2014). While partial-cutting is mainly viewed in the literature as one of the key treatments to implement under climate change, it should be viewed as a complementary tool to clear-cutting rather than a wholesale replacement to take advantage of the environmental assets provided by both interventions (Nagel et al. 2017; Prichard et al. 2021; Lafond et al. 2024).

There is still limited understanding of how climate change will impact landscape-level attributes under the combined use of clear-cutting, partial-cutting, and other silvicultural practices, as well as how these methods can be optimized for long-term management objectives. The increasing scientific preference for partial-cutting over clear-cutting has sparked debate in the Acadian forest region, including New Brunswick, Nova Scotia, and Maine, primarily due to the reduced wood fiber supply associated with partial-cutting (Lahey 2019; Minister of Natural Resources and Energy Development 2023). However, strategically combining clear- and a variety of partial-cutting has the potential to modify harvest composition and maintain a balanced flow of forest resources, helping to sustain forest values in an uncertain climate future (Ashton and Kelty 2018; Lafond et al. 2024).

While silvicultural interventions are recognized as a potential tool for adapting forests to climate change, significant gaps remain in understanding how they influence key stand- and landscape-level outcomes such as forest structure, wood supply, and economic performance. Additionally, optimizing the scheduling of these practices under future climate scenarios is not yet well established. To address these gaps, this study evaluates the effectiveness of different silvicultural strategies at the landscape scale under climate change, considering forest inventories and wood supply, economic factors, and

environmental trade-offs. Using the stand-level process-based model, PICUS (Lexer and Hönninger 2001; Seidl et al. 2011), we simulated stand dynamics for twelve stand types under a range of silvicultural regimes across three climate scenarios from the Intergovernmental Panel of Climate Change 5th assessment report (Baseline, RCP4.5 and RCP8.5). These simulations were used to generate climate-sensitive yield tables and transition rules for each silvicultural intervention. These data then served as inputs for Woodstock (Remsoft 2023), a forest management planning model and decision support system used to conduct strategic planning on forest landscapes. Woodstock was then used to simulate the management of a 67,000 ha forest landscape located near Fredericton, New Brunswick, in the central Acadian forest. By applying an optimization algorithm, the model identified optimized intervention schedules to achieve management objectives under the different climate scenarios.

4.2. Material and methods

4.2.1. Study landscape

The management situation occurred on the planning unit of the 5th Canadian Division Support Base - Gagetown (hereafter referred to as 'Gagetown') in southern New Brunswick, Canada. Gagetown's forest covers approximately 87,000 ha (77% of that landbase was modeled) and experiences a temperate-continental climate, characterized by cold winters and warm summers, with mean temperatures of -6°C in January and 14°C in July. Annual precipitation averages 1 200 mm, with 25% occurring during the growing season (June–August).

The area is ecologically diverse, with site productivity varying from well-drained, nutrient-rich floodplains to acidic podzols, and elevations ranging from sea level to 420 meters. The forest landscape has been primarily shaped by anthropogenic disturbances. Over the last century, human-caused fires have burned approximately 2 500 ha, while timber harvesting has occurred at a rate of around 400 ha per year since 1985. These disturbances have resulted in a forest composition dominated by shade intolerant and mid-shade-tolerant tree species including red maple (*Acer rubrum* L.) at 25%, a mixture of red (*Picea rubens* Sarg.), white (*Picea glauca* (Moench) Voss), and black spruce (*Picea mariana* (Mill.) B.S.P.) at 22%, balsam fir (*Abies balsamea* (L.) Mill.) at 15%, trembling aspen (*Populus tremuloides* Michx.) at 7%, and white birch (*Betula papyrifera* Marshall) at 4%. Some other species such as tamarack (*Larix laricina* K. Koch), red oak (*Quercus rubra* L.), red pine (*Pinus resinosa* Sol.), white ash (*Fraxinus americana* L.) and red (*Pinus resinosa* Ait.) and white pine (*Pinus strobus* L.) are present, but in low quantities.

4.2.1.1. Characterizing the forest landscape inventory

We stratified the landscape into twelve distinct stand types based on average species composition (Figure 4.1A), as identified through a LiDAR-based enhance forest inventory conducted in 2018 by the Department of Natural Resources and Energy Development of New Brunswick. The given names of each stand type corresponded to their initial tree species composition, even though this composition will change over time, especially under various climate scenarios. The inventory data were captured at a 20 m resolution and scaled-up to the stand-level by calculating the weighted average of area of each cell within each stand polygon (the LiDAR-based enhanced forest inventory is structured as a

20 × 20 m raster grid, while traditional inventory polygons are irregular and vary in shape and size).

The balsam fir mixedwood (BFMX) stand type was the most prevalent at Gagetown, covering 22% of the area, followed by white birch mixedwood (BIMX) and poplar hardwood (POHW), each representing 18% (Figure 4.1B). The intolerant softwood (INSW) stand type covered an additional 14%, highlighting the predominance of shade-intolerant species across the working forest landscape. Together, these four stand types make up nearly three-quarters of the total forest area. The remaining 28% included various other stand types, tolerant mixedwood (THMX), white pine softwood (WPSW), pure black spruce (BSPR), balsam fir, tolerant hardwood, spruce mixedwood (SPMX), mixed spruce softwood (MXSP), and birch hardwood (BIHW; Figure 4.1B).

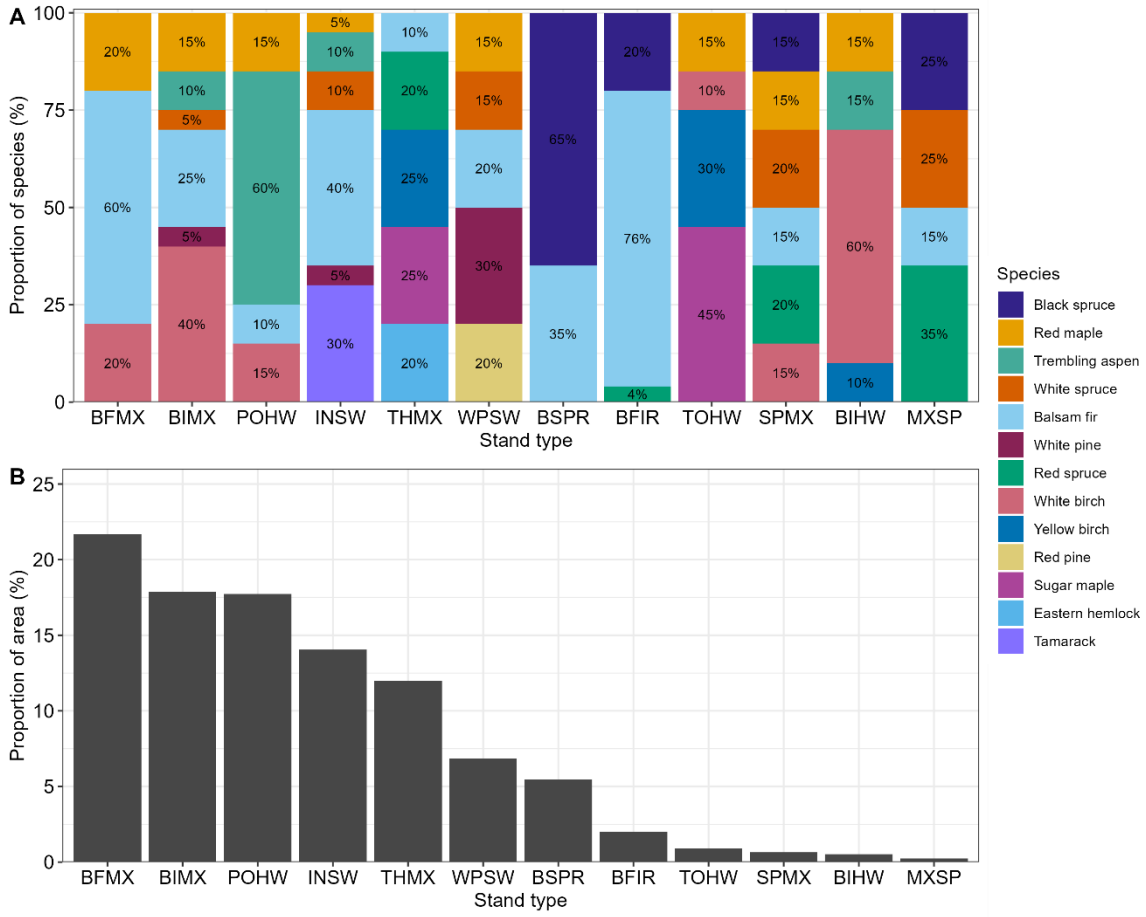


Figure 4.1. Study area forest inventory. **A)** Species composition of each stand type used in the initialisation phase of stand-level modeling. **B)** Proportions of stand types represented within the study area. Note: BFIR = balsam fir, BFMX = balsam fir mixedwood, BIHW = birch hardwood, BIMX = white birch mixedwood, BSPR = black spruce, INSW = intolerant softwood, MXSP = mixed spruce softwood, POHW = poplar hardwood, SPMX = spruce mixedwood, TOHW = tolerant hardwood, THMX = tolerant mixedwood, WPSW = white pine softwood.

4.2.2. Stand-level modeling simulation design

4.2.2.1. Description of model

To simulate climate-sensitive forest stand dynamics and provide the input needed for the landscape analysis, we used the PICUS stand simulation model (version 1.5; Lexer and Hönninger 2001; Taylor et al. 2017). PICUS is a spatially explicit, process-based simulation model designed to simulate the growth, establishment, and mortality of individual trees within forest stands on annual time steps under varying environmental conditions, including climate change. The model operates on 10 × 10 m forest patches, typically arranged in grids ranging from 100 to 1 000 patches, corresponding to stand areas of 1-10 ha. Key features of PICUS include its 3D light distribution module, which accounts for spatially explicit interactions among trees, as well as explicit seed dispersal processes. Climate and soil conditions are applied uniformly across the grid, while light availability and tree demographics vary between patches. PICUS has been calibrated and validated for the Acadian forest region, a detailed description of its parameterization is available in Taylor et al. (2017).

4.2.2.2. Model limitations

While PICUS is well suited for projecting forest stand dynamics under climate change, it has notable limitations. It struggles with simulating extreme climatic events and prolonged droughts (Lexer et al. 2002). Although a disturbance module exists, PICUS lacks a detailed framework for modeling pest infestation gradations, limiting its ability to capture their full impacts (Seidl et al. 2008). Specifically, for the Acadian forest, PICUS does not account for the effects of beech bark disease (*Neonectria faginata*), which affects over 90%

of American beech (*Fagus grandifolia*; Taylor et al. 2013; Stephanson and Ribarik Coe 2017). Furthermore, the model's dependence on comprehensive site and stand-level input data creates challenges in areas with incomplete data coverage, often requiring reliance on regional average data values and expert opinion (e.g. Taylor et al. 2017; Albert et al. 2024).

4.2.2.3. Upscaling PICUS outputs

To evaluate the effects of silvicultural interventions at the landscape-level for different climate change scenarios, the PICUS stand-level outputs were organized into stand yield tables and transition rules for use in the forest landscape model, Woodstock. Yield tables are essential for forecasting stand attribute development over time, offering detailed predictions of key metrics such as stand volume, height, basal area, and species composition. When assigned to their associated stand types, these tables provide the structured data required to simulate forest landscape dynamics under different management and environmental scenarios (Bettinger et al. 2016). In this case, yield tables were constructed and summarized using 5-year planning period (i.e., time step) intervals to describe change in stand type dynamics over the course of the planning horizon used in Woodstock.

For integration at the landscape-level, stand type specific yield tables and transition rules were linked to specific forest stands in the inventory. These yield tables and transition rules provide Woodstock the detailed information required to simulate the stand inventory following scheduled silvicultural interventions. Albert et al. (2024) developed a detailed methodology to connect stand-level information with landscape-level modeling in Woodstock by generating climate-adapted yield tables that incorporate transition periods

and accounted for annual change in climate. For specifics on the development of yield tables and transition rules, see Section 4.2.2.4, and for their integration into Woodstock, refer to Section 4.2.3.

4.2.2.4. Stand type initialization in PICUS

PICUS was initialized for each unique stand type to simulate those stand types and produce the necessary stand dynamics data. In this study, PICUS simulations were initialized as 1 ha stands of young tree saplings (1.3-2 m tall) for each stand type with densities ranging from 5,000 to 10,000 stems per hectare. The species composition for each stand type simulation was determined by the tree species composition present in the stand inventory of each stand type within the study area (Figure 4.1A). PICUS also requires estimates of average soil conditions typically associated with each stand type, including pH, available nitrogen ($kg \cdot ha^{-1} \cdot year^{-1}$), and water-holding capacity (field capacity in mm). Due to limited availability of such detailed soil records, these parameters were derived from interpolated spatial soils data provided by Mansuy et al. (2014) and uniform soil values were applied across all stand types, with pH set at 5, water-holding capacity at 75 mm, and available nitrogen at 95 $kg \cdot ha^{-1} \cdot year^{-1}$.

PICUS simulates stand dynamics using monthly time-series climate data, which were obtained from high-resolution (1 km) interpolated climate grids provided by Natural Resources Canada, downscaled from regional climate models (McKenney et al. 2011). In this study, we used three climate forcing scenarios: a baseline scenario without climate change, representing mean climate during the 1981–2010 reference period, and two climate change scenarios, RCP4.5 and RCP8.5, using forecast data obtained from the Canadian

Earth System Model version 2 (CanESM2) and using the representative concentration pathways (RCPs) from the AR5 report (Intergovernmental Panel on Climate Change et al. 2015). The RCP4.5 scenario forecasted a warming of + 4°C by 2100, while the RCP8.5 scenario anticipated a more severe warming of + 7°C by 2100 within the study area. These two climate change scenarios are approximately equivalent to the corresponding AR6 shared socio-economic pathways (SSPs) SSP2-4.5 and SSP5-8.5 respectively (Intergovernmental Panel on Climate Change et al. 2023).

4.2.2.5. Integrating climate into yield tables and transition rules

We followed the methods of Albert et al. (2025) to dynamically simulate the effects of climate change on stand yield and transition rules. Specifically, we developed age-class-specific yield tables for stands aged 0-25, 25-50, 50-75, and 75+, while also accounting for future changes in regeneration patterns by dividing transition rules into three periods: 2020-2050, 2050-2080, and 2080-2110. These age groups and transition periods remained consistent across all intervention simulations and climate scenarios. Stand-level simulations were run for 120 years to capture the full effects of climate change on stand conditions, and the resulting yield tables were then input into Woodstock (see section 4.2.3 below). Yield tables for all interventions were constructed by averaging the outputs of 30 unique PICUS simulations, all of which were run under identical settings. This approach addresses the inherent stochasticity within the model, which arises due to random processes governing stand dynamics, such as species regeneration and mortality patterns.

PICUS output variables included in the yield tables included tree stem density (stem·ha^{-1}), basal area (m^2·hectar^{-1}), merchantable volume per species (m^3·hectar^{-1}), and

wood product ratios (% of total volume). Wood product ratios (Honer 1893; Kershaw et al. 2007) needed product specifications to be calculated. These specifications were determined based on average mill specifications for facilities neighboring the study area, compiled from the Southern New Brunswick Forest Products Marketing Board (2024). For simplicity, wood products were categorized into four product classes for both coniferous and deciduous species based on minimum top end log diameter and length specifications: sawlogs, studwood, pulpwood, and biomass (Table 4.1). For deciduous species the top two larger products can be defined as high- and low-quality sawlogs but for simplicity will be referred to as sawlogs and studwood hereafter.

Table 4.1. Wood product specifications used in yield table development. Note: diameters measurements are inside bark.

Product	**Coniferous species**		**Deciduous species**	
	Minimum diameter (cm)	Product length (m)	Minimum diameter (cm)	Product length (m)
Sawlogs	18	5.05	20	2.55
Studwood	12	2.55	15	2.55
Pulpwood	8	2.55	8	2.55
Biomass	1	> 1	1	> 1

4.2.2.6. Description of silviculture intervention

We simulated three silvicultural interventions across the three climate scenarios to evaluate their effects on forest dynamics and yield: 1) clear-cutting (100% harvested), 2) low-retention partial-cutting (40% harvested), and 3) high-retention partial-cutting (10% harvested). Post-harvest conditions for each intervention were modeled using species-specific regeneration rules associated with three transition time periods: 2020–2050, 2050–

2080, and 2080–2110. These rules were developed from the PICUS outputs and predicted post-intervention species composition and regeneration levels.

Clear-cutting represented the most intensive intervention, involving the removal of 100% of merchantable trees with no specific selection order. Stands were becoming operable with clear-cutting as soon as they reached a minimum of 100 $m^3 \cdot ha^{-1}$; however, the optimal harvest timing past this point was determined by Woodstock.

Low-retention and high-retention partial-cutting aimed to remove 40% and 10% of the total basal area, respectively. These interventions followed a species prioritization sequence designed to favor species better suited to future climatic conditions. The prioritization, informed by prior research (Taylor et al. 2017; Albert et al. 2025), removed species that are expected to be the most vulnerable to climate change, namely: balsam fir, black spruce, jack pine (*Pinus banksiana* Lamb.), white spruce, red spruce, trembling aspen, sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), eastern cedar (*Thuja occidentalis* L.), eastern hemlock (*Tsuga canadensis* (L.) Carrière), and red maple. PICUS harvests trees sequentially from the beginning of this list until the target basal area removal is achieved. To reduce modelling time, we only produced partial-cut yield tables and transitions for eight of the twelve stand types (i.e., BFMX, BIMX, BSPR, INSW, POHW, THMX, TOHW, and WPSW), which combined represented 97 % of the total study area. Partial-cutting occurred at pre-determined intervals based on age-class-specific yield tables. For instance, for stands aged 0–25 and 25–50, harvests were conducted at age 40; for stands aged 50–75, at age 60; and for stands aged 75+, at age 125. For stands regenerated during the 2050–2080 or 2080–2110 time periods, harvesting occurred at age 40 regardless of age class. These timings were selected through sensitivity

analyses of post-harvest stand responses and visual inspection of resulting yield tables which showed that volume accumulation and species composition stabilized around this age. Earlier or later harvest ages resulted in lower yields or limited species responses.

4.2.3. Landscape level model simulation setup – Woodstock

4.2.3.1. Description of model

Woodstock (Remsoft 2023) is a forest management planning model and decision support system used to conduct strategic level planning on forest landscapes. It applies advanced mathematical techniques, such as linear programming, to address complex optimization problems involving the scheduling and regulation of management activities across large landscapes, that must satisfy multiple objectives and constraints.

Woodstock also uses land classification schemes called "THEMES" to link the forest landscape stand inventory and the stand type yield tables and transition rules. Woodstock has been widely used in forestry research to explore diverse aspects of forest management and economics (e.g., Lantz et al. 2007; Lundholm et al. 2020; Dymond et al. 2020).

All Woodstock model files, and input data (including data for yield tables and transitions rules, and version 1.5 of PICUS) have been deposited in the UNB Dataverse Repository to ensure transparency and reproducibility: https://doi.org/10.25545/ZHZJHV. Interested researchers can access and explore the models and data for further analysis or replication.

4.2.3.2. Model limitations

Woodstock has several limitations. The quality of forecasts depends on the availability and quality of the inputted yield tables and transition rules, which in this case are provided by PICUS (McLarin et al. 2006). The model also simplifies or, in some instances, excludes complex processes such as fire spread, insect infestations, and disease outbreaks, which limits its ability to account for important aspects of landscape ecology (Lundholm et al. 2020). Further, Woodstock does not directly account for spatial constraints, such as adjacency and opening rules, which define the properties of typical harvest blocks (groups of contiguous stands) designated for silvicultural interventions. Finally, the model's interface and coding structure present a steep learning curve for new users, requiring extensive training and expertise to use effectively (St. Jean Conti 2008).

4.2.3.3. Implementation of silviculture in Woodstock

Woodstock relied on the yield tables and transition rules produced by PICUS (Section 4.2.2) to forecast landscape attributes and their relationship with climate change. In Woodstock, changes in forest landscape conditions are calculated by determining the difference between pre-intervention and post-intervention yield tables. The reaction of stands to silviculture interventions is triggered by intervention-specific and stand-specific transition rules. For clear-cutting, stand-age is reset to zero after a harvest, as 100% of tree basal area is removed. The wood volume harvested during a clear-cut is equal to the stand’s total volume at the time of harvest. Following clear-cutting, the stand develops along a new stand development trajectory defined by the corresponding yield table (originally derived from the PICUS simulations). In contrast, partial-cutting occurs at predefined entry times

during stand development, and stand-age is not reset to age zero after the intervention. The volume harvested during partial-cutting intervention is a fraction of the stand's initial volume, averaging 40 % for low-retention harvests and 10% for high-retention harvests. Post-intervention, partial-cut stands continue to develop according to the yield tables associated with that specific stand-type following partial-cutting.

4.2.3.4. Landscape stratification and scenarios

To evaluate the effects of climate change on the landscape using Woodstock, we developed three distinct management scenarios in Woodstock using the PICUS-derived climate sensitive yield tables. Each scenario was constructed with a unique set of yield tables and transition rules reflecting the three climate scenarios: baseline, RCP4.5, and RCP8.5. We parametrized Woodstock with five stratification themes: 1) stand origin (i.e. natural, retention harvest), 2) stand type, 3) initial age class, 4) climate transition period, and 5) climate scenario, to link each forest stand to the correct yield table during the initialization phase. Each unique permutation of these theme parameters represents a unique development type in Woodstock.

In each management scenario, the objective was to maximize the stumpage revenue from wood product sales (a price list is provided in Table 4.2 based on the New Brunswick Timber Regulation 86-160 (2024)) while maintaining an even flow of harvested volume over a 100-year simulation period. In the study area, the Government of Canada acts as both landowner and decision maker, directly receiving stumpage revenues from timber sales. Variations in stumpage revenue are influenced by the selection of silviculture intervention by Woodstock, as each intervention and their timing influence the provision

of wood products, thus modifying the revenue results of the objective function. For each Woodstock scenario, the linear programming optimization problem was solved using the proprietary software, MOSEK version 10.

Table 4.2. Price list of wood product by species utilized in the optimization.

Species	Products	Price ($\$\cdot m^{-3}$)
Balsam fir Black spruce Jack pine Red spruce Black spruce Tamarack	Sawlogs	40.60
	Studwood	33.58
	Pulpwood	6.80
	Biomass	2.00
Red maple Red oak Sugar maple Yellow birch White ash White birch	Sawlogs	24.25
	Studwood	20.78
	Pulpwood	20.78
	Biomass	2.00
Red pine White pine	Sawlogs	15.50
	Studwood	15.50
	Pulpwood	3.43
	Biomass	2.00
Trembling aspen	Sawlogs	20.78
	Studwood	20.78
	Pulpwood	8.07
	Biomass	2.00
Eastern white cedar	Sawlogs	8.07
	Studwood	8.07
	Pulpwood	8.07
	Biomass	2.00

4.2.3.5. Landscape management simulation outputs

Landscape outputs describe the overall state of the forecasted landscape based on the application of scheduled interventions and the natural development of each stand. For this

analysis, the outputs were categorized into four main groups: silvicultural, inventory, economic, and other environmental considerations (Table 4.3). Further, explanation about how each output has been developed is provided in Table 4.3.

We created three outputs to report the level of silvicultural activity occurring over the landscape-level simulation (Table 4.3). The area of silvicultural interventions (ha) represents the total area treated with each merchantable silvicultural intervention (i.e., clear-cut, low-retention harvest, and high-retention harvest). The proportion of silvicultural interventions (%) indicates the relative contribution of each intervention based on the treated area. Lastly, the volume of merchantable product harvested (m^3) quantifies the volume harvested under each silvicultural intervention.

To describe the landscape forest inventory and species composition, we created three additional outputs (Table 4.3). The operable inventory volume (m^3) records the volume still available for harvest at the end of a planning period. The species composition in inventory (%) describes the tree species composition of the standing inventory based on volume. Similarly, the species composition of harvested wood products (%) reflects the species composition of the harvested volume under silvicultural interventions.

To assess economic factors over the entire forecast period, we created three outputs based on stumpage prices presented in Section 4.2.3.4 (Table 4.3). The stumpage revenue ($) reports the monetary revenue generated from silvicultural interventions. The present value ($) measures the profitability of forecasted scenarios using a 4% interest rate. Finally, the proportion of stumpage revenue by wood product (%) indicates the contribution of each forest product to the total revenue from harvested volume.

We also developed three outputs to evaluate other potentially important environmental considerations associated with natural disturbances and diversity, which are influenced by management practices and climatic conditions (Teshome et al. 2020; Hartmann et al. 2022; Albert et al. 2023; Table 4.3). These indicators were designed to give forest managers an estimate of the potential risks associated possibly originating from their landscape management over the long-term. First, the fire consideration output is based on two metrics: the area of young forests (aged 0–29 years) and the area dominated by deciduous species, representing the proportion (%) of the forested landscape resistant to fire (Hevia et al. 2018; Jain et al. 2020). Second, the species richness (unique tree species per stand on average) assesses general tree species diversity. This indicator is calculating the average number of unique tree species per stand within the managed landscape as higher diversity increase stands tolerance to various stressors and reduce vulnerability (Messier et al. 2022). Lastly, the drought output quantifies the forest area dominated (>50%) by so-called drought-tolerant species as identified by Pearson and D'Orangeville (2022) and represents the proportion (%) of the forested landscape more resistant to drought conditions under climate change (white pine, red oak, jack pine).

Table 4.3. Landscape-level outputs and descriptions.

Output category	Output name	Output description
Silvicultural Intervention	Area of silvicultural interventions	Sum of the total area treated (ha) by each silvicultural intervention during each 5-year planning period.
	Proportion of silvicultural interventions	Percentage (%) of silvicultural interventions represented by the sum of the area treated by each intervention divided by the total area treated, multiplied by 100.

	Volume of merchantable product harvested	Sum of the volume of merchantable wood harvested (m^3) from each silvicultural intervention during each 5-year planning period.
Forest Inventory	Operable inventory volume	Total merchantable volume available (m^3) for harvesting at the end of each 5-year planning period based on the operability of areas eligible for silviculture intervention (see section 4.2.2.5).
	Species composition in inventory	Percentage of tree species in the inventory represented by the sum of the volume (m^3) of each tree species, divided by the total volume in inventory, multiplied by 100.
	Species composition of harvested wood products	Percentage of each tree species in the overall volume of wood harvested by silviculture treatment represented by the sum of the volume (m^3) of each tree species, divided by the total volume in inventory, multiplied by 100.
Economic Impacts	Stumpage revenue	Sum of wood volume harvested of each wood product multiplied by their corresponding stumpage price for each 5-year planning period ($; see Table 4.2).
	Present value	Present value ($) is the sum of stumpage revenues over the planning horizon discounted at 4 % per year to the present time.
	Proportion of stumpage revenue by wood product	The percentage (%) of each wood product's contribution to total stumpage revenue; calculated by summing the total volume and stumpage revenue associated with each harvested wood product, then dividing the revenue of each wood product by the total revenue for each 5-year planning period, multiplied by 100.
Other Environmental Considerations	Fires	Proportion (%) of area resistant to fires defined by the area of 0-29-year-old forest plus the area of over 30-year-old pure deciduous and mixed-deciduous forest (conifer content < 50%) divided by the total area and multiplied by 100.
	Species richness	Species richness is defined as the total number of unique tree species within each stand. This value is then averaged across all stands in the landscape to determine the average species richness per stand.
	Droughts	Proportion (%) of area resistant to droughts defined by the area dominated (> 50% abundance) by drought-tolerant species: white pine, red oak, jack pine (Niinemets and Valladares 2006).

4.3. Results

4.3.1. Silvicultural interventions and responses

4.3.1.1. Stand-level dynamics

Using stand-level model PICUS, we generated 16 stand yield tables per stand type for each silvicultural intervention, accounting for initial stand age groups, transition time periods, and climate scenarios. We simulated 12 stand types for the clear-cut intervention and 8 stand types for high- and low-retention silviculture interventions (four stand types, MXSP, BIHW, SPMX, and BFIR, were excluded from the retention harvest modelling because they closely resembled other stand types in composition of already modelled stands and represented less than 3.5% of the managed area, making them an inefficient use of modelling resources; one day of simulation for completely modelling each stand types under all the conditions of the stratification used), totaling 448 yield tables and an equal number of transition rules to represent both the current and future of stands in the Gagetown planning unit (Figure 4.2; see Figure S4.1; S4.2; S4.3 for all yield tables and transitions).

The clear-cutting intervention significantly altered species composition and reduced post-harvest species diversity as the climate warmed under both climate change scenarios (Figure 4.2). Red maple dominated over 90% of stand composition under both RCP4.5 and RCP8.5 following clear-cutting from 2050 onwards when initial stand composition was greater than 15% red maple. White pine and yellow birch emerged as the next most competitive species to regenerate and develop following clear-cutting under climate change, particularly in stands where they initially represented more than 10% of the pre-harvest forest composition (Figure S4.1). The low-retention silvicultural intervention,

which removed 40% of tree basal area, had a greater impact on species composition, particularly in tolerant hardwood mixedwood stands, where sugar maple was largely removed due to its higher harvest priority in this treatment, inhibiting its regeneration and promoting eastern hemlock under baseline and RCP4.5 climate scenarios (Figure 4.2, THMX panels). When warming exceeded 3°C during the 2050-2080 period of both climate change scenarios, low-retention harvesting seemed to accelerate declines in total volume, limiting regrowth compared to clear-cutting. In contrast, high-retention harvesting, removing only 10% of basal area, had minimal impact on total standing volume over the modelling period, with no major changes observed in most cases (Figure 4.2, Figure S4.2).

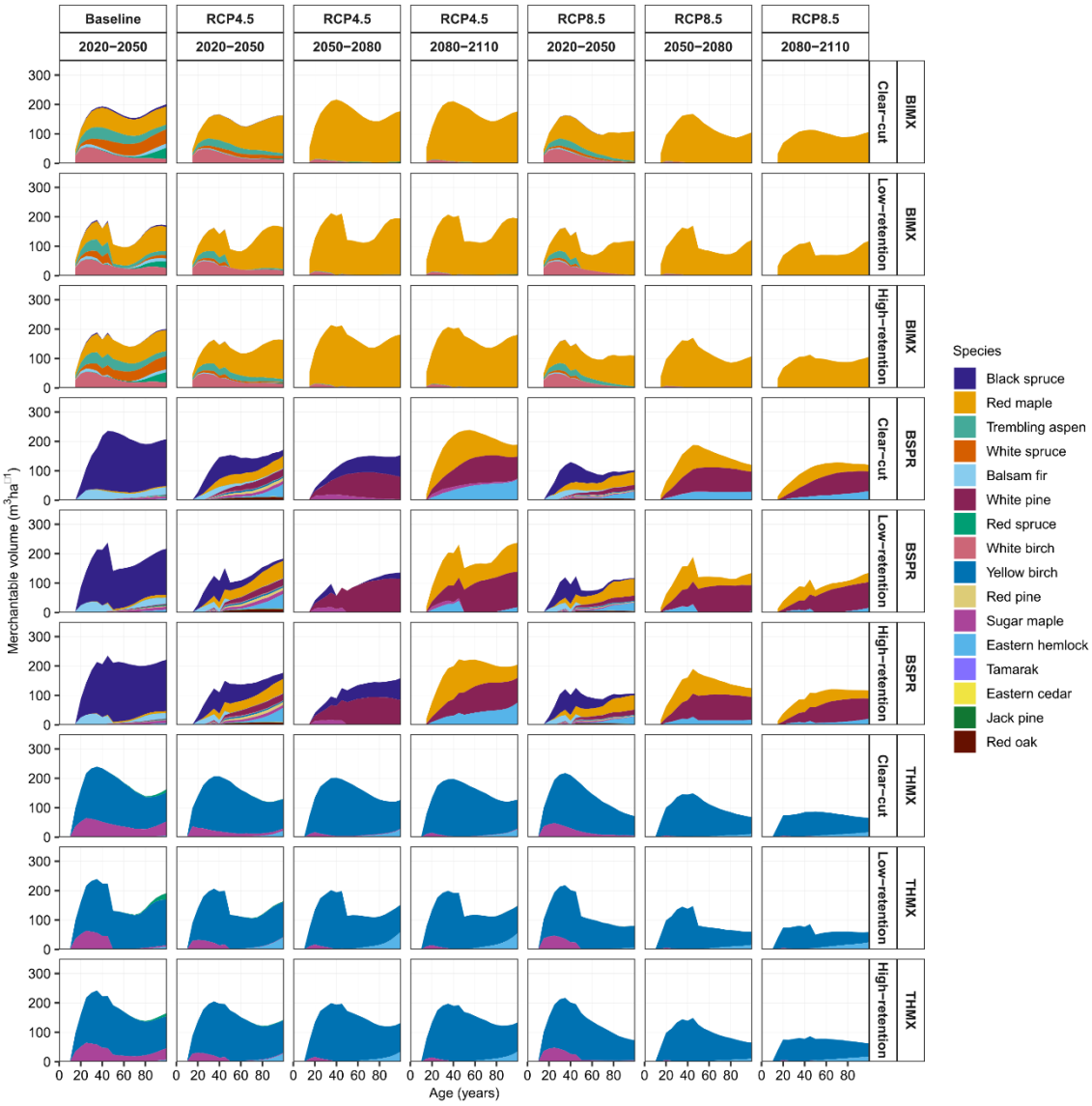


Figure 4.2. Forecasted merchantable volume and species composition over time with PICUS for white birch mixedwood (BIMX), pure black spruce (BSPR), and tolerant hardwood mixedwood (THMX) stands under different silvicultural interventions (clear-cut, high-retention, low-retention) and climates (baseline, RCP4.5 and RCP8.5). Note: Clear-cut intervention displays post-harvest data, while high- and low-retention interventions show post-intervention data from age 40 onward since the intervention occurs at that age for the 0-25 age group shown here).

4.3.1.2. Landscape-level dynamics

Once the stand-level PICUS outputs were implemented in Woodstock, it permitted us to make landscape-level forecasts which took into consideration the three climate scenarios and silvicultural interventions. Correspondingly, Woodstock optimized silviculture intervention schedules to maximize stumpage revenues over a 100-year planning horizon under each of the climate scenarios. Since the objective function in this planning model was to maximize stumpage revenue under climate change, several fundamental principles should be recognized to understand the silvicultural scheduling formulated by Woodstock: (1) the greater the harvested volume (m^3), the higher the stumpage revenue; (2) the higher the value ($) of harvested wood products, the greater the stumpage revenue; and (3) clear-cutting yields greater harvested volume per unit area compared to partial-cutting (Figure 4.2). However, since stands that undergo partial-cutting (i.e., low- and high-retention harvests) eventually become eligible for clear-cutting 10 years after the initial partial-cutting entry, and because the operational criteria for partial-cutting differ from clear-cutting, allowing stands to be available for harvest at different times, Woodstock strategically increasingly utilizes high-retention partial-cutting followed by clear-cutting treatments as a silvicultural regime under climate change. This approach, combined with improved stand responses following partial-cutting, enables an overall greater harvest within the same timeframe compared to just clear-cutting alone, thereby enhancing the stumpage revenue for the objective function.

Detailed analysis of the optimized silviculture intervention schedules showed that clear-cutting was the dominant intervention across all climate scenarios, though its frequency of use declined with increasing temperatures. Although total harvested area

remained stable at ~ 2300 ha across scenarios (< 2% variation; Figure 4.3B), the share of that area allocated to clear-cutting decreased by up to 5%, with high-retention harvesting correspondingly increasing under warmer climates (Figure 4.3A). Under baseline climate, clear-cutting accounted for 77 ± 24% of annual harvested area (1826 ± 650 ha), decreasing slightly under RCP4.5 to 1803 ± 712 ha (a 1.2% reduction; Figure 4.3A). Under RCP8.5, clear-cutting declined further, dropping to 72 ± 23% of annual harvested area (Figure 4.3A).

Of the two partial-cutting treatments part of the silviculture intervention schedules in this study, high-retention partial-cutting emerged as the preferred method, as it contributed the most to achieving the objective function, when included in a sequence of partial-cutting followed by clear-cutting. High-retention harvesting remained relatively stable across all climate scenarios, contributing to an average 22 ± 25% of harvested area under the baseline climate scenario, with similar levels scheduled under RCP4.5. However, under RCP8.5, its share increased to 1.2 times the baseline and RCP4.5 levels, averaging 564 ± 480 ha annually (Figure 4.3A). On the other hand, low-retention harvesting was primarily used near the end of the planning horizon when there was insufficient time to implement the high-retention-clear-cutting sequence, and the targeted stands have not yet met the operability criteria for clear-cutting. Low-retention harvesting was the least utilized intervention, representing < 1% of annual harvested area under baseline climate scenario. Under RCP4.5, the intervention was only scheduled to occur during the 2115-2120 time period, where it increased to 530 ha annually, 1.4 times the baseline average rate. Under RCP8.5, it followed a similar pattern but with a greater expansion in the final five years of planning (845 ha annually); apart from a small 10 ha treatment application in 2035, there

was a 2.3-fold increase in low-retention harvesting relative to the baseline scenario (Figure 4.3A).

Despite the increase in high-retention harvested area (Figure 4.3A), total harvested volumes fell by 6% under RCP4.5 and 10% under RCP8.5 relative to the baseline, driven by reduced growth of cold-adapted boreal species (balsam fir, white spruce, trembling aspen, white birch; Figure 4.3C; D). From 2025 to 2060, clear-cut volumes declined by 4% (RCP4.5) and 9% (RCP8.5), high-retention volumes dropped by 15% in both scenarios, and low-retention volumes remained essentially unchanged. During 2065–2120, clear-cut harvested volumes diverged further declining by 10% under RCP4.5 and 21% under RCP8.5, while partial-harvest treatments increased, high-retention volumes rose by 4-10% and low-retention volumes by 15-64% compared to baseline (Figure 4.3C).

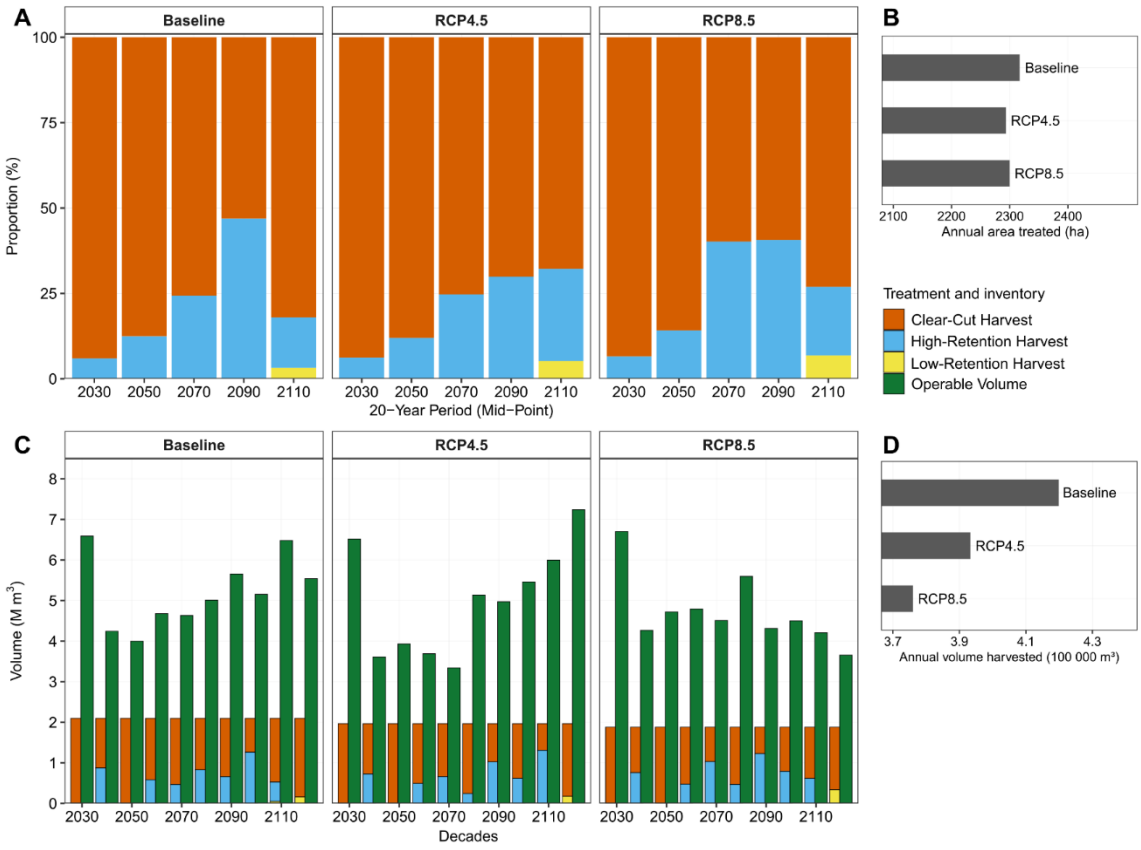


Figure 4.3. Silviculture related metrics. **A)** Proportion of the total area (ha) of silviculture interventions occurring on the landscape averaged over 20-year time periods. **B)** Annual area treated on average for each climate scenario. **C)** Average volume harvested per 5-year (million m^3) by silvicultural interventions for each decade and operational inventory available at the end of each 5-year period of every decade. **D)** Annual volume harvested on average for each climate scenario.

4.3.2. Forest inventory changes

The total operable forest inventory for silviculture interventions (which represent the total amount of volume (m^3) available for harvest) generally declined under climate change, despite concurrent reductions in harvested volume under climate change scenarios

relative to baseline. The operable average volume of 5.2 Mm^3 under baseline climate decreased to 4.9 Mm^3 under RCP4.5 (an approximate 4% reduction) and to 4.7 Mm^3 under RCP8.5 (an approximate 9 % reduction; Figure 4.3C). These declines in operable volume under climate change scenarios are driven by an overall reduction in stand productivity, which, when combined with harvesting (especially clear-cut and low retention harvest), further exacerbates the decrease. However, during the 2110-2120 period under RCP4.5, the operable available volume was higher than under other scenarios for the same period. This projected increase in operable volume suggests an increase in stand-level performance of some tree species (i.e., yellow birch, white pine, and red maple) and wood supply under RCP4.5 (see Figure 4.2 for examples) beyond the bottleneck period of 2045-2065 (Figure 4.3C).

The species composition of the landscape shifts over time under climate change relative to the baseline scenario, with red maple emerging as a dominant species under both RCP4.5 and RCP8.5 by the end of the planning horizon (Figure 4.4A). Under baseline conditions, red maple constituted, on average, only 22 ± 4% of the inventory, but increased to 25 ± 1% under RCP4.5 and 28 ± 3% under RCP8.5 during the early time period of 2020-2040. By mid-century (2060–2080), its share rose significantly to 43 ± 13% under RCP4.5 and 41 ± 7% under RCP8.5, compared to 19 ± 3% under the baseline scenario. Over the long term (2100-2120), red maple comes to dominate the landscape under climate change, accounting for 61 ± 5% under RCP4.5 and 68 ± 9% under RCP8.5 (Figure 4.4A). Conversely, white spruce decreased from 14 ± 2% under the baseline scenario to 5 ± 2% under RCP4.5 and 4 ± 1% under RCP8.5 by mid-century, and to less than 1% by 2100-2120 (Figure 4.4A). Trembling aspen followed a similar trend, dropping from 14 ± 3%

under the baseline scenario to 8 ± 6% under RCP4.5 and 7 ± 1% under RCP8.5 by mid-century, and to less than 1% by 2100. Warmer adapted yellow birch and white pine showed modest gains in abundance, with yellow birch increasing from 7 ± 2% under the baseline scenario to 11 ± 4% under RCP8.5 by mid-century, and white pine becoming more prominent on the landscape increasing from 10 ± 1% under the baseline to 14 ± 3% during the 2100-2120 time period of both RCP scenarios (Figure 4.4A).

The species composition of harvested wood volumes reflects changes in the composition of forest inventory, with increasing volumes of temperate deciduous species harvested over time. During the 2020-2040 time period, red maple accounted for 28 ± 16% of harvested volume under the baseline climate scenario. It was slightly less at 25 ± 9% under RCP4.5, but higher at 32 ± 19% under RCP8.5 (Figure 4.4B). By mid-century (2060-2080), the share of red maple harvested rose to 23 ± 9% under RCP4.5 and to 32 ± 10% under RCP8.5, compared to 14 ± 7% under the baseline for the same time period. By 2100-2120, red maple dominated the harvested wood volume, reaching 85 ± 15% under RCP4.5 and 69 ± 30% under RCP8.5. In contrast, the volume of trembling aspen harvested was 26 ± 13% under the baseline scenario but had declined to 14 ± 12% under RCP8.5 by mid-century and was absent completely by 2100-2120. Similarly, white spruce decreased from 9 ± 8% in the baseline to 3 ± 3% under RCP8.5 by 2020-2040 and was absent from harvested volume by the end of the planning horizon. White pine rose from 7 ± 6% in the baseline scenario to 21 ± 20% under RCP8.5 by mid-century, though its share of the harvested volume remained relatively low over the long term, while yellow birch decreased from 16 ± 15% under baseline to 6 ± 8% under RCP8.5 by mid-century but recovered to 17 ± 2% by 2100. Overall, temperate deciduous tree species increasingly dominated

harvested volume over time, even under baseline scenario, showing an increase from 52 ± 20% in the 2020-2040 time period to 74 ± 18% in the 2100-2120 time period. However, the rise in temperate deciduous volume harvested was faster and greater under RCP4.5, going from 54 ± 10% (2020-2040) to 97 ± 0% (2100-2120), while RCP8.5 showed a similar but more variable trend, increasing from 55 ± 18% (2020-2040) to 90 ± 10% (2100-2120).

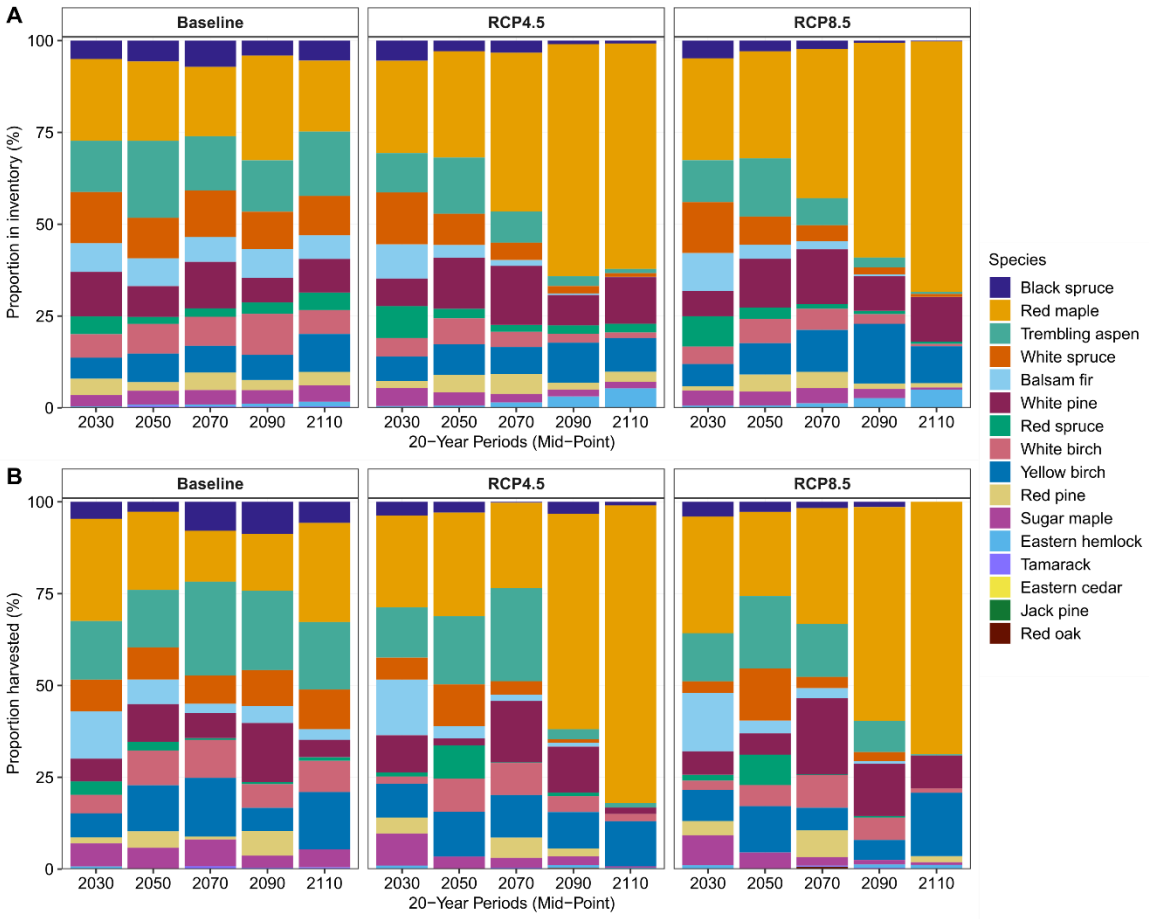


Figure 4.4. Proportion of tree species based on merchantable volume. **A)** Forest landscape inventory. **B)** Volume harvested.

4.3.3. Economic impacts

Climate change driven shifts in species composition and product mixes on the landscape negatively impacted stumpage revenue flow across the planning horizon and scenarios (Figure 4.5). Stumpage revenue under baseline climate averaged $9.2 ± 0.6 million · year^{-1}, fluctuating between a minimum of $8 million · year^{-1} (2050-2055) and a maximum of $10.7 million · year^{-1} (2115-2120; Figure 4.5A), while under RCP4.5 and RCP8.5 the average stumpage revenue declined by 12-16% to $8.1 ± 0.8 million · year^{-1} and $7.7 ± 0.8 million · year^{-1}, respectively. Under RCP4.5, revenue peaked earlier at $10 million (2035-2040) before falling to $7.9 ± 1.0 million · year^{-1} (2045-2120), and under RCP8.5 revenue rose up to $10.5 million · year^{-1} (2040-2045) then dropped to $7.4 ± 0.9 million · year^{-1} on average through 2120. These overall trends are driven by shifts in product mix (Figure 4.5B): in the baseline scenario, pulpwood, studwood and sawlogs contributed 27 ± 17%, 39 ± 8 % and 33 ± 19% of revenue until ~ 2080, when sawlogs rose to 60 % as pulpwood declined. Under RCP4.5, sawlogs accounted for only 19 ± 11% of the first 30 years stumpage revenue versus studwood 57 ± 6%, but from 2040 onward sawlogs climbed to 26 - 42% reaching 50% by 2120 as studwood stabilized around 33 ± 9 %. RCP8.5 followed a similar trajectory but with lower sawlog share (37% by 2120). Using a 4 % discount rate, the present value fell from $247.8 million (baseline) to $226.6 million (-8.6%) under RCP4.5 and $218.2 million (-11.9%) under RCP8.5, reflecting both reduced harvested volumes and changing product mixes.

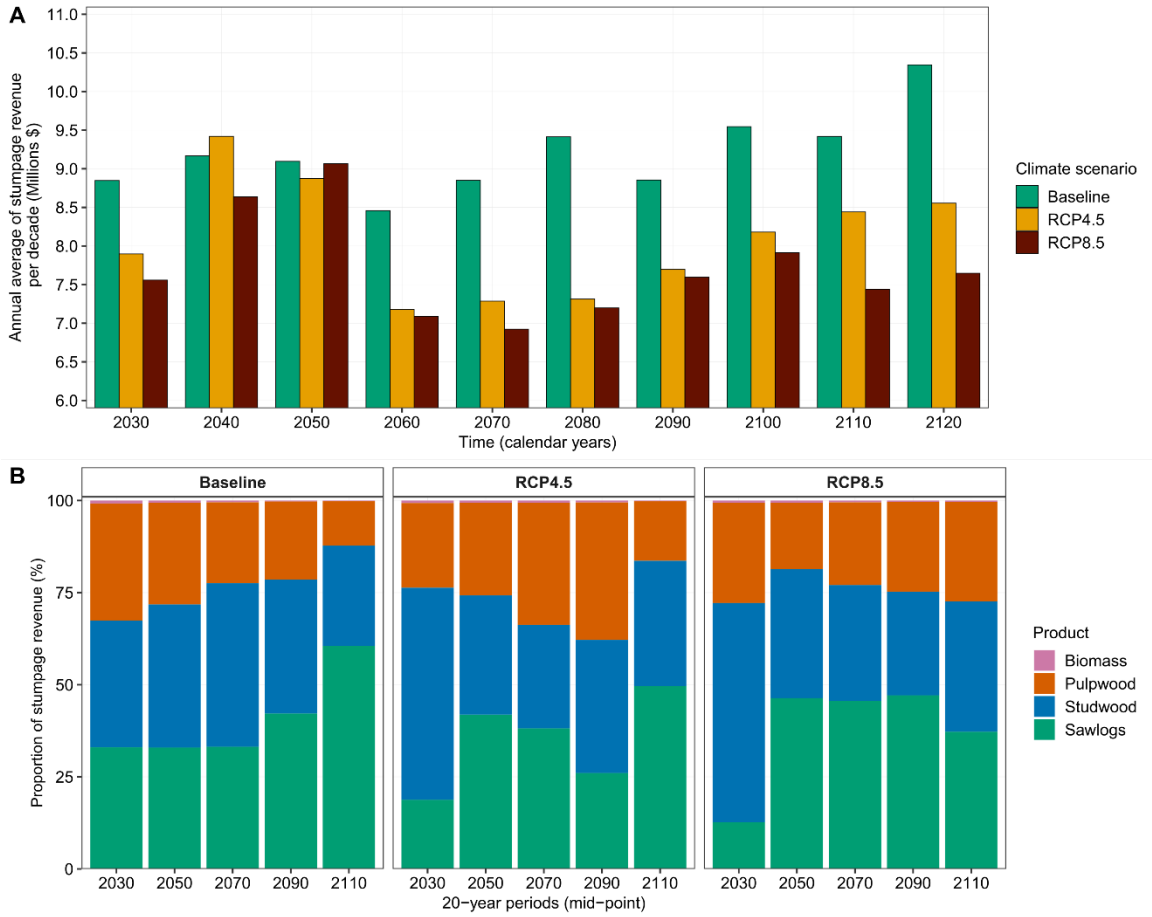


Figure 4.5. Change in financial indicators across the study area **A)** Stumpage revenue generated from the harvest of wood product averaged for each decade of the planning period. **B)** Proportion of wood products contributing to stumpage revenue.

4.3.4. Environmental considerations

Throughout the first 65 years of the planning horizon, the proportion of fire-resistant forest area (based on the abundance of young, deciduous-dominated forest stands) showed no statistically significant difference between baseline and RCP scenarios (Figure 4.6A). However, between 2080 and 2120, fire-resistant forest area temporarily significantly increased by 15% under both RCP4.5 ($p = 0.029$; significance from the Wilcoxon Signed-

Rank statistical test) and RCP8.5 ($p = 0.048$), driven by the increased abundance of young deciduous stands. This gain was not sustained however, and by the final decades of the planning horizon, fire-resistant area declined to 10% below the level observed in the baseline scenario due to increasing pine species dominance.

Average tree-species richness per stand declined under both RCP4.5 and RCP8.5 relative to the baseline (Figure 4.6B), driven by the expanding dominance of red maple and the progressive loss of cold-adapted boreal species. Under RCP4.5, diversity was 0.5 ± 0.3 species less by the end of the planning horizon compared to the baseline scenario, while under RCP8.5 it was 1.25 ± 0.2 species less, particularly after the year 2070. Although some recovery of species richness occurred after 2100 for the RCP scenarios, it did not return to baseline levels.

Drought tolerance, measured as the forest area dominated by drought-tolerant tree species white pine, red oak and jack pine (representing > 50% of total stand volume), showed a statistically significant increase ($p = 0.016$) between 2040 and 2070 under both RCP scenarios compared with baseline climate scenario (Figure 4.6C). A 10% increase was observed under RCP4.5, while RCP8.5 showed a more modest 5% gain. However, these changes were reversed after the year 2070, where by 2110, drought-tolerant area fell by 4% and 7% below the baseline scenario for RCP4.5 and RCP8.5, respectively.

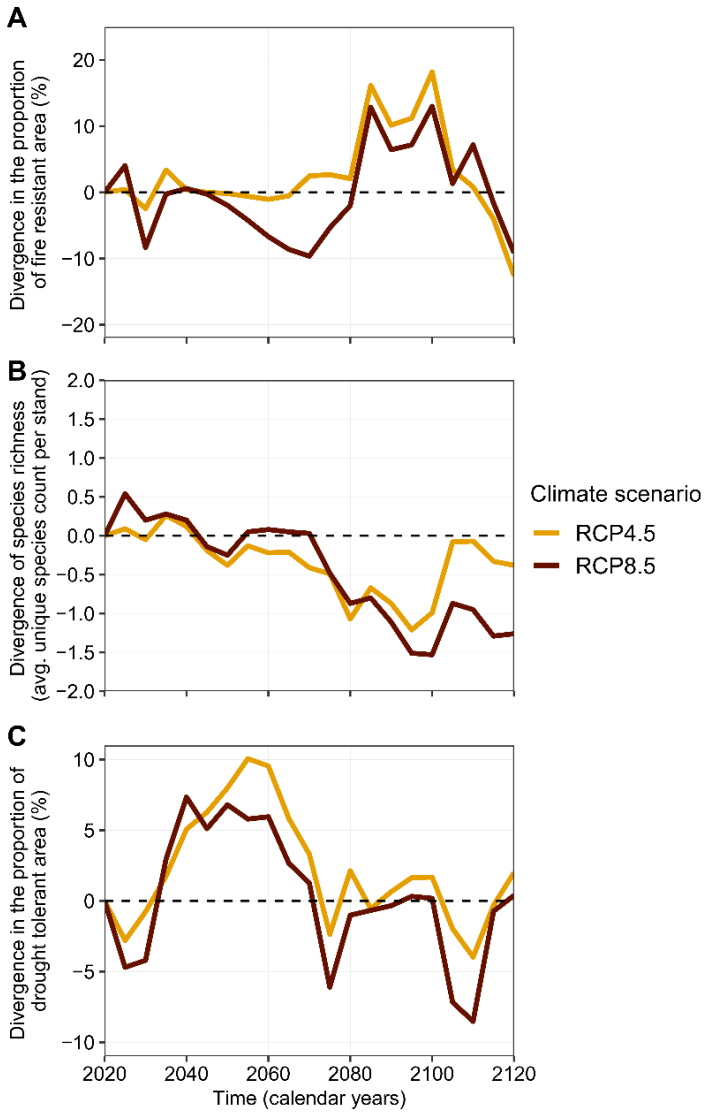


Figure 4.6. Environmental considerations for natural disturbances and diversity divergence from the baseline scenario. **A)** Proportion of the area at risk of fire. **B)** Average stand species richness (unique tree species average count). **C)** Proportion of the area tolerant to drought.

4.4. Discussion

Despite their importance in the sustainable management of forest resources, few studies have examined the effects of climate change on silvicultural activities, wood supply, and financial returns. Using a process-based, stand simulation model to generate climate sensitive yield tables applied to a forest management planning model and decision support system, we show that climate change will substantially impact strategic-level forest management planning by lowering sustainable harvest volumes, increasing the proportion of broadleaf species in the fibre supply, and maintaining clear-cutting as the dominant intervention, increasingly coupled with high-retention partial harvest.

4.4.1. The influence of climate change on silviculture scheduling

Whereas studies conducted in North American boreal and Acadian forests have identified partial cutting as a key treatment to mitigate the impacts of climate change on fibre supply and economic returns (Salmon et al. 2016; Molina et al. 2022a; Girona et al. 2023), partial-cutting is also frequently favored for its ability to maintain soil moisture, support species richness, and stabilize microclimatic conditions (Salmon et al. 2016; Greiser et al. 2024; Zhang et al. 2024). Since the most severe shifts in Acadian forest landscape dynamics, as well as declines in stumpage revenues and fibre flow, only occur after 2060, partial-cutting treatments become more prominent beyond that point. These findings align with those of Ameray et al. (2023), who showed that integrating partial-cutting strategies helps maintain forest goods and services in eastern Canadian forests, because post-harvest growing conditions are less vulnerable to climate change stressors. Several studies also emphasize the importance of silvicultural diversity to buffer the

impacts of climate change on forest productivity (e.i., Park et al. 2014; Nagel et al. 2017; Albert et al. 2023). This is supported in our study by the relatively stable forest inventory across scenarios, in contrast to the > 50% decline observed in Albert et al. (2025) when only clear-cutting was used under RCP8.5. Moreover, shifts toward retention-style harvesting, which aim to balance timber yield with conservation goals, have also been highlighted as an adaptive strategy (Kuuluvainen et al. 2012; and Cherubini et al. 2018).

Nonetheless, while our modelling suggests that clear-cutting can remain a viable option under projected climate conditions, this contrasts with other studies indicating that it may increase regeneration failure risks and reduce diversity under climate change (Taylor et al. 2020a; Suzuki et al. 2021). These differences may arise from variations in study focus, scale, and methodological assumptions. Our landscape-level model operates across broader spatial and temporal scales and includes stumpage revenue optimization. In contrast, studies that emphasize ecological outcomes, such as regeneration, diversity, or growth rate, often focus on stand-level dynamics and exclude economic optimization, potentially amplifying the perceived risks of clear-cutting by overlooking its primary economic advantage. Empirical evidence supports these concerns. For example, White et al. (2024) found that forest management reduced local species diversity in the Acadian forest, although this effect was offset at the landscape scale by species influx from other areas. However, our results suggest that this broader diversity could still be at risk if climate change disproportionately reduces populations of less common species, particularly under the increasing dominance of red maple observed in our simulations. Similarly, Bowd et al. (2023) documented that frequent clear-cuts are likely to result in regeneration failure. Additionally, Taylor et al. (2020a) based on an analysis of over 19 000 stands, also found

that clear-cutting favors the growth of shade-intolerant deciduous species (e.g., red maple) at the expense of shade-tolerant conifers (e.g., spruce spp.). Our results reflect this compositional shift: the strategic planning model could not sustain the more economically valuable shade-tolerant species indefinitely but used retention harvests to delay the shift and reduce its economic impact. Finally, our findings are consistent with economic studies showing that clear-cutting tends to remain the preferred treatment under most conditions, even when alternatives are available, unless forest conditions become severely degraded by the practice (Tahvonen 2015; Pukkala 2016; Eggers et al. 2020).

To our knowledge, no recent study has directly examined shifts in the use of silvicultural treatments using optimization under climate change at the landscape planning level in north America. However, some optimization studies have reported variation in optimal rotation lengths under climate change, depending on the dominant species composition in each stand. Rotations tend to be shorter when climate-induced growth improves and longer when growth declines (Pukkala and Kellomäki 2015; Zell and Hanewinkel 2015). These findings are consistent with our results: rotation lengths had to be extended under both climate forcing scenarios to meet the minimum clear-cutting threshold of 100 $m^3 \cdot ha^{-1}$, particularly under RCP8.5. Similarly, the use of high-retention partial cutting, followed by clear-cutting as the final harvest, contributed to longer rotations while minimizing the loss of value due to climate change.

4.4.2. Consequences of climate-driven change on forest composition and harvesting

We found a substantial shift in species composition away from cold-adapted species (e.i., white spruce, balsam fir, and trembling aspen) under warming which is consistent

with other studies of eastern North American forests that used PICUS as their stand model (Taylor et al. 2017; Brecka et al. 2020). Similar shifts have also been reported using other climate-sensitive stand-level models in the Acadian forest such as ZELIG-CFS (Elzein et al. 2020; Larocque et al. 2024) and at the landscape level with LANDIS-II (Molina et al. 2022b; Liang et al. 2023).

The shift in species composition is expected to alter the type of wood fibre supplied to processing mills, transitioning from conifer-dominated to deciduous-dominated sources. This has significant implications for the forest sector in eastern Canada. For example, conifer wood supply has accounted for over two-thirds of the total in New Brunswick (> 6 $Mm^3 \cdot year^{-1}$) and Québec (> 23 $Mm^3 \cdot year^{-1}$) since the early 2000s (CCFM 2005; BFEC 2020). This abundance of conifer supply has led to a predominance of conifer-processing mills, consequently, the sector now depends on a steady conifer supply, which is increasingly challenged by climate change. In our study, because conifer products had higher stumpage value (see section 4.2.3.4), the landscape-level planning model optimized interventions to maximize conifer harvests. Partial harvesting was used to slow the transition toward lower-value deciduous fibre products by leveraging the "blocking effect" described by Taylor et al. (2017). This effect occurs when maladapted species occupy growing space and temporarily delay the establishment of better-adapted but lower-value deciduous species. Other studies projecting a landscape-level shift toward deciduous species have raised similar concerns about potential conifer fibre shortages and overall fibre supply reductions (e.i, Boulanger and Pascual Puigdevall 2021; Lantz et al. 2022; Wotherspoon et al. 2024).

The economic repercussions observed in this climate-adapted strategic forest planning study, specifically, a 12-16% decline in stumpage revenue, were primarily driven by the increasing dominance of temperate deciduous species within harvested volumes. These findings are broadly consistent with other modeling studies focused on the Acadian forest region (Lantz et al. 2022; McMonagle et al. 2024; Albert et al. 2025). Specifically, Lantz et al. (2022) used an economic and forest management planning model to evaluate climate change impacts on fibre supply and the economy in New Brunswick. They linked a 6% reduction in total timber supply under RCP8.5 by 2095, comparable to our 9% decline by 2120, to an economic output reduction ranging from 0% to 11%, depending on the sector. Their less pronounced economic impact likely reflects the incorporation of dynamic pricing based on wood product scarcity, an adjustment not accounted for in our model. Building on this, it is reasonable to expect that the scarcity of cold-adapted conifer products will drive up their market value, while an oversupply of deciduous products may exert downward pressure on prices, thereby influencing future treatment scheduling and management decisions (Asada et al. 2023). Similarly, Halpin et al. (2024) reported negative economic outcomes and reduced forest productivity under climate change, suggesting that retention harvesting could help sustain forest value, a strategy further supported by the results we found.

A sensitivity analysis was conducted to address concerns that the Woodstock model may be biased in favour of partial harvesting, as it initially applied the same stumpage rate to partial treatments as to clearcutting (Figure 4.7). To reflect the higher operational costs typically associated with partial cutting, which vary across jurisdictions and ownership types, stumpage rates for retention harvest treatments were progressively reduced. Even

when stumpage was set to $0 for partial treatments, these remained active, particularly under climate change scenarios (RCP4.5 and RCP8.5) however, they barely got used under the baseline (Figure 4.7). Under RCP8.5, a sharper decline in the use of high-retention treatments was observed only below 75% of the clearcut stumpage rate, suggesting that modest reductions (less than 25%) have more limited effect on treatment selection. Under the baseline scenario, this threshold was closer to 95% (Figure 4.7). Analysis of the sensitivity of schedule activities indicate that partial harvests provide strategic value by facilitating access to more valuable clearcuts that will follow partial harvests, reinforcing the study's main findings that the used of partial harvest increase under climate change. The analysis also confirms the optimizer's responsiveness to economic signals when maximizing stumpage revenue with different stumpage rate by treatment.

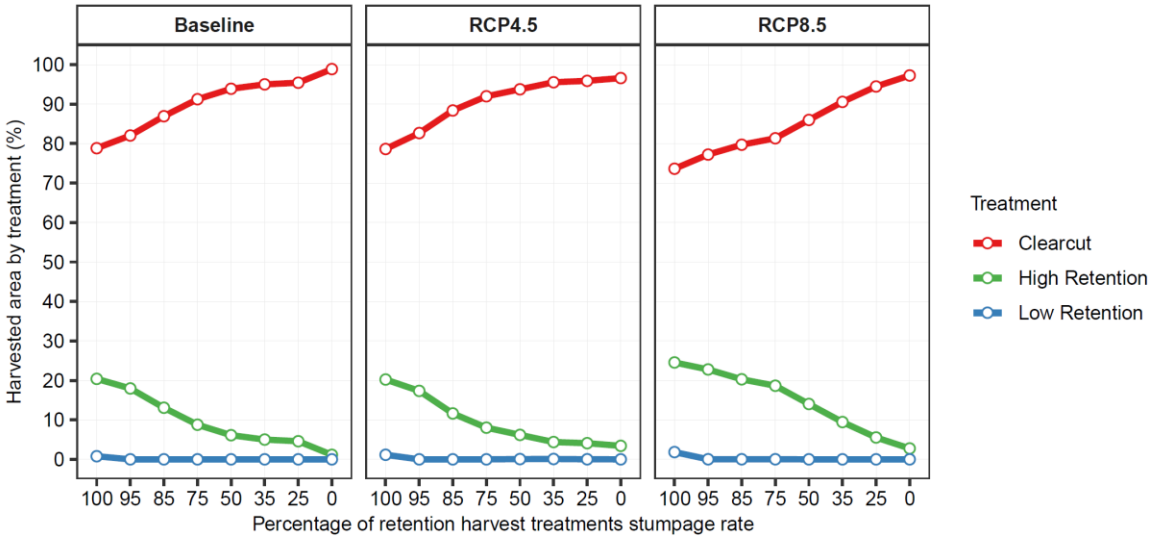


Figure 4.7. Sensitivity analysis of the effect of retention harvest stumpage rate on the proportion of harvested area by treatment across climate scenarios. Note: The stumpage rate for clearcut treatments remains fixed at 100%, while the stumpage rate for retention harvest treatments varies along the x-axis.

Although the objective function used in this study does not maximize present value, it is important to acknowledge that the choice of discount rate can influence economic evaluations, particularly in cost-benefit analyses of silvicultural investments. In line with the Treasury Board of Canada's recommendation for regulatory proposals, an 8% discount rate is often used to reflect opportunity costs of capital and to ensure conservative financial assessments rater than a 4% rate. However, in the context of this study, where the optimization model is based on maximizing total stumpage revenue rather than discounted cash flow, adjusting the discount rate would not affect harvest scheduling outcomes. The model's treatment selection is instead driven by relative stumpage values, wood supply dynamics, and operational constraints over time. Nonetheless, future work incorporating present value based objective functions or evaluating silvicultural investments in more detail could benefit from explicit testing of discount rate sensitivity.

4.4.3. Landscape resilience under climate change

Climate-driven shifts in tree species composition and productivity raise concerns about the future resilience of forest ecosystems (Taylor et al. 2017; Brecka et al. 2020; Messier et al. 2022). Since the introduction of cold-adapted conifer plantations in the Acadian forest during the 1940s-1960s, species composition has shifted away from its historical diversity, resulting in a greater dominance of cold-adapted conifers (Noseworthy and Beckley 2020). This shift has increased forest vulnerability to fire and insect outbreaks (Jain et al. 2020; Noseworthy and Beckley 2020). However, we observed a reversal of this trend (i.e., a “deborealization”) in the latter part of the simulation horizon, primarily due to the poor performance of spruces and balsam fir and the increasing dominance of temperate

species such as red maple and yellow birch. Similar declines in vulnerability under warming climates have been reported (Duveneck and Scheller 2016; Lucash et al. 2017; Frelich et al. 2020), with some studies proposing vulnerability indicators (Cantarello et al. 2017; Bryant et al. 2019; Rammer et al. 2021). For instance, Bryant et al. (2019) linked resilience to structural attributes like basal area, showing that stands outside their historical range are less likely to recover. This aligns with our results, where red maple dominance exceeding 50 % of total forest volume indicates a shift beyond historical variability. Furthermore, the rise of temperate broadleaf species eventually led to a reduction in fire risk across the managed landscape, though only after 2080–2110. Before that, the planning model prioritized maintaining conifer presence as long as possible to benefit from the "blocking effect." This strategy led to the accumulation of older, maladapted, and fire-prone conifer-dominated stands prior to 2080. These findings are consistent with studies predicting similar species trajectories in eastern North America and linking them to fire risk (Boulanger et al. 2021). Boulanger et al. (2013) specifically used the conifer component as the main predictor combined with climate variables to predict fire risk. This underscores that the conifer accumulation observed in our results could significantly increase fire risk. Maintaining conifer composition under warmer climates, despite their maladaptation, may worsen forest fire impacts and threaten future fiber supply (Boulanger et al. 2019).

4.4.4. Limitations and conclusion

While this study focused on the effects of climate change on forest stand dynamics, and its impacts on strategic forest management planning, this study did not consider the

effects of climate change on the occurrence and damage from natural disturbances, such as wildfire, windthrow, and pest outbreaks (e.g., spruce budworm; *Choristoneura fumiferana* Clemens). Some of these disturbances are expected to intensify under warmer climate (Taylor et al. 2020b), further affecting wood supply (Seidl et al. 2011; Thomas et al. 2024). For example, Boulanger et al. (2013) predicts the area burned in eastern Canada to more than double under climate change over the next couple decades. Damage from windthrow is also expected to increase as extreme wind events (e.g., hurricanes) become more severe in eastern Canada (Taylor et al. 2020b). Forest openings caused by clear-cutting may exacerbate this by exposing neighboring stands (Guimond et al. 2024); however, use of partial-cutting may also decrease the windfirmness of stands if removal is too high or treatments are conducted in site with high wind exposure (Ruel 1995; Gardiner et al. 1997). Likewise, some invasive insect pests such as the Asian longhorned beetle (*Anoplophora glabripennis* Motschulsky), the hemlock woolly adelgid (*Adelges tsugae* Annand), and the forest tent caterpillar (*Malacosoma disstria* Hübner), may become more prevalent as climate warming is expected to reduce mortality rates as reported by Hunt et al. (2006) and Rustad et al. (2012).

Assisted migration is increasingly recognized as a key adaptation strategy to mitigate the negative impacts of climate change on ecosystem services and economic output (Williams and Dumroese 2013; Sáenz-Romero et al. 2021), and trials are currently underway across North America (e.g., Royo et al. 2023). The biodiversity loss observed in this study could be offset by the arrival of new species, either naturally or through assisted migration. However, the silvicultural toolbox developed in this study does not incorporate assisted migration, despite promising results for several species, such as white spruce, that

exhibit potential for climate change mitigation (Sáenz-Romero et al. 2021). The primary reason for this exclusion is the limited calibration of stand-level models to capture the growth potential of different populations within a species (Gray et al. 2011; Williams and Dumroese 2013). Future research should focus on improving the calibration of these models to support the integration of assisted migration into climate-adapted strategic forest management plans. The results we found are also highly contingent on the stumpage prices used in this study. While they are reflective of today's local prices, pricing will change over time and will affect harvest scheduling and overall outcomes. However, because sawlogs usually, consistently command higher prices than pulpwood and biomass, the potential for major shifts in results due to price fluctuations seems limited. Another limitation of this study lies in how partial-cutting treatments are simulated in PICUS to generate yield tables. PICUS removes tree species sequentially based on a predefined priority list, which does not fully reflect real-world harvesting practices. In practice, mechanical harvesting cannot selectively remove single species as precisely due to the need for harvest trails, which function as small-scale clear-cuts (Kizha et al. 2021). Additionally, the stand-level simulations assumed constant soil water-holding capacity, available nitrogen, and pH across all climate scenarios. However, these factors are likely to change with climate through various biophysical processes, potentially affecting both stand- and landscape-level dynamics. Further research is needed to assess how climate-driven soil variations could influence future forest composition and productivity.

Although the 10% retention harvest treatment was useful for exploring the effects of low-intensity partial harvesting in the optimization framework, its operational implementation using conventional forestry equipment presents significant limitations. In

practice, achieving a uniform 10% canopy removal is only feasible through manual harvesting or using specialised equipment. When using traditional large, mechanized equipment, the equivalent removal would typically involve establishing one 10 m trail every 100 m, creating a spatially clustered disturbance pattern rather than the randomly (relatively uniform) distributed canopy openings simulated in the PICUS stand model. This type of treatment may currently be more appropriate for small-scale woodlots, where manual or low-impact harvesting techniques are more common.

Despite its limitations, this study provides critical insights into how climate change may affect forest management planning strategies, economic outcomes, and the ecological resilience of forest landscapes in the Acadian forest region. By integrating a sophisticated, stand-level process-based model, capable of simulating the effects of climate change on stand dynamics, into a landscape-level strategic forest planning model and decision support system, the analysis we conducted suggests that a combination of partial-harvest treatments and clear-cutting will be necessary to sustain the provision of forest goods and services under climate change. While partial-cutting offers ecological benefits, economic constraints will likely sustain the dominance of clear-cutting over the next century. Hence, developing a diverse silvicultural toolbox will help forest managers mitigate climate change impacts on fiber supply and forest values by carefully adjusting the timing and scale of interventions. Ultimately, this work serves as both a guide and a cautionary perspective for long-term landscape decision-making, equipping forest managers with insights to navigate the evolving balance between economic objectives and ecological values in a rapidly changing climate.

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Supplementary material

This supplementary material includes:

Figure S4.1. to Figure S4.3.

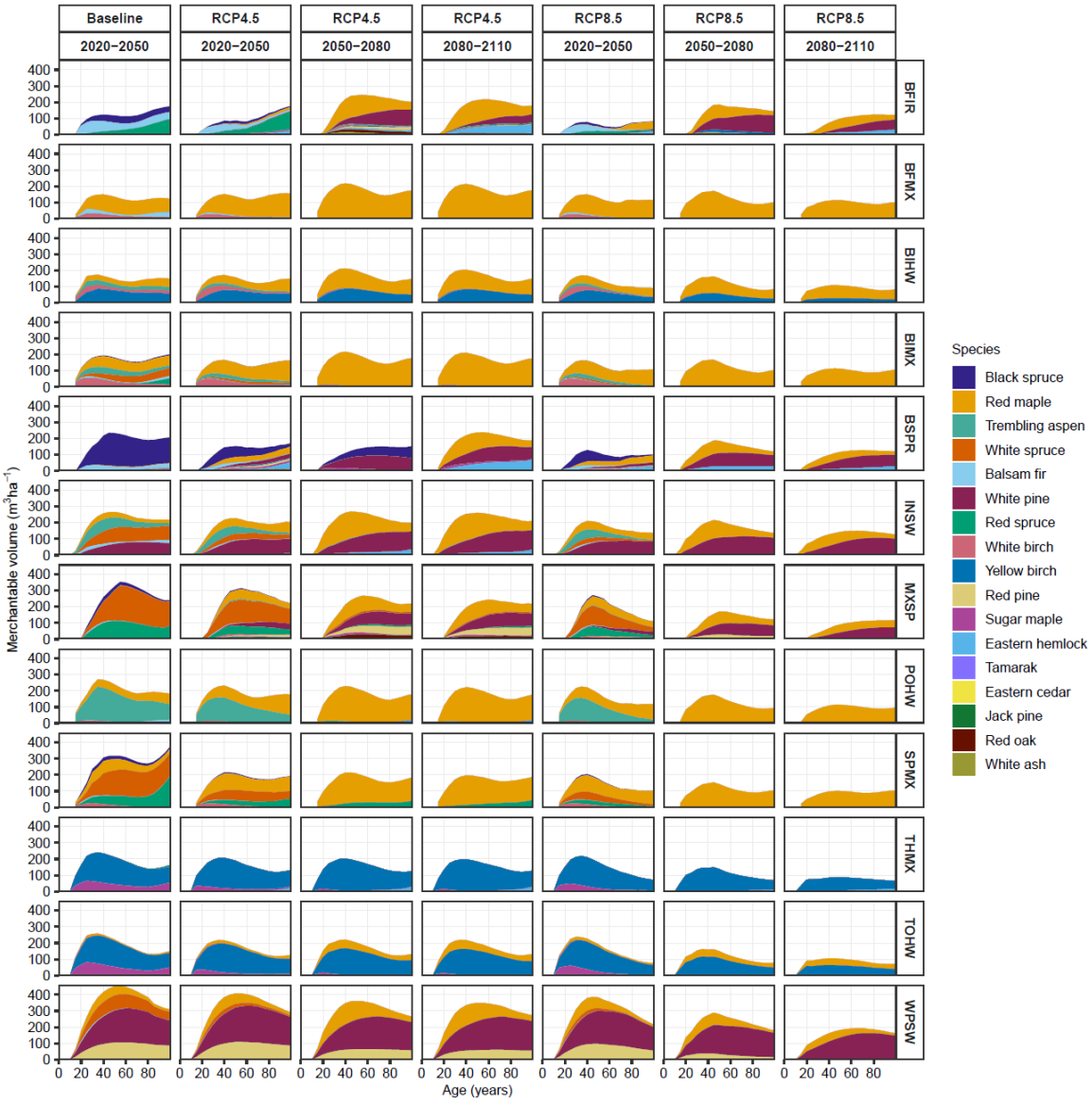


Figure S4.1. Projected merchantable volume and species composition in stand level projections by PICUS over time and three climate scenarios (baseline, RCP4.5 and RCP8.5) following the clear-cut silviculture treatment.

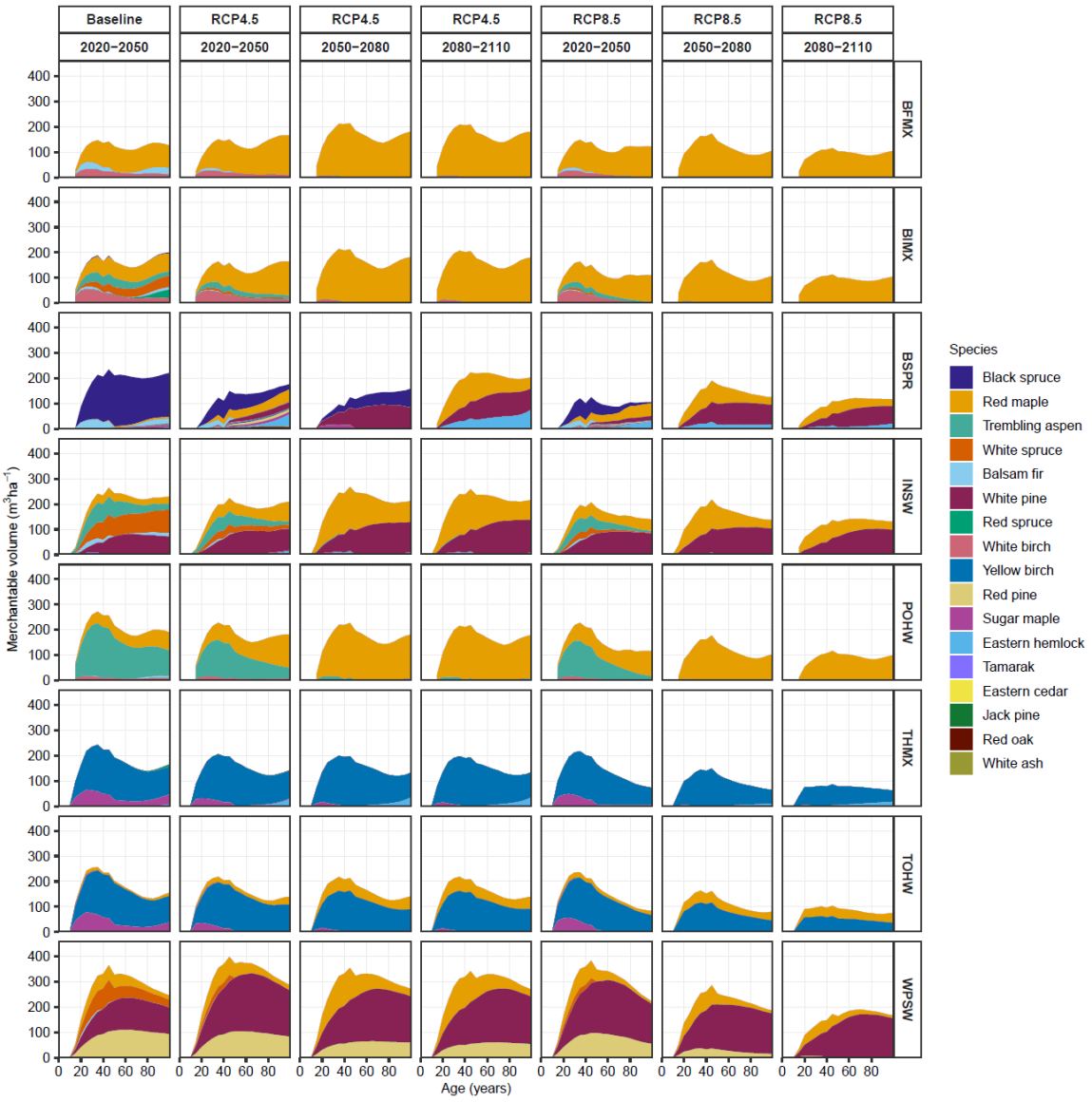


Figure S4.2. Projected merchantable volume and species composition in stand level projections by PICUS over time and three climate scenarios (baseline, RCP4.5 and RCP8.5) following the high-retention silviculture treatment occurring at 40-years old.

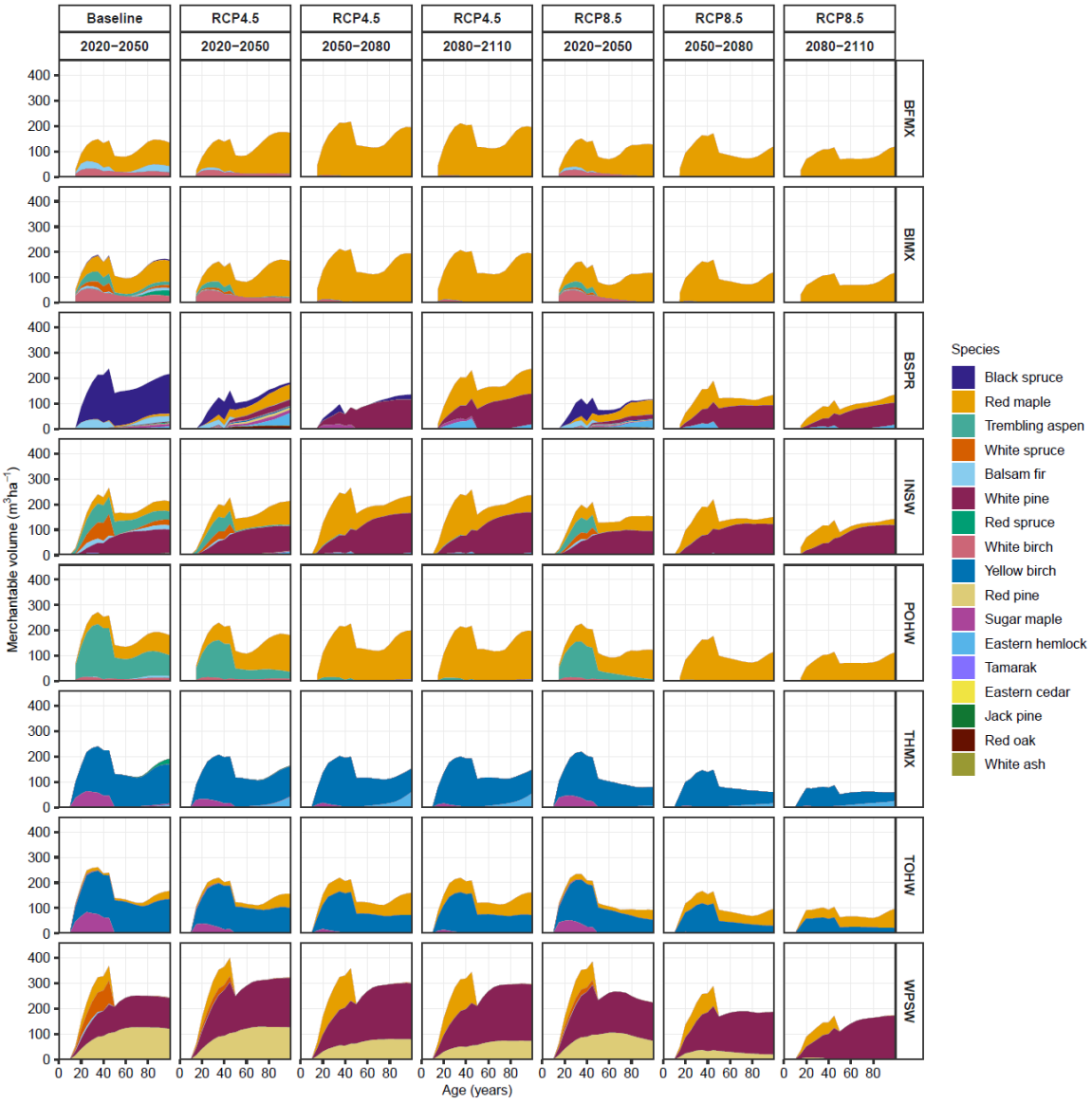


Figure S4.3. Projected merchantable volume and species composition in stand level projections by PICUS over time and three climate scenarios (baseline, RCP4.5 and RCP8.5) following the low-retention silviculture treatment occurring at 40-years old.

Chapter 5. General discussion

5.1. Discussion and implications

The research presented in this thesis underscores the profound implications of climate change on forest ecosystems, productivity, and management practices, specifically within the Acadian forest region. This discussion synthesizes insights and the methods (Table 5.1) from research chapters 1, 2, and 3, creating a cohesive narrative that bridges ecological observations, methodological advancements, and strategic applications to bring forward the adaptation of strategic forest planning to climate change. These research chapters were dependent on each other for the following reasons: (1) Adapting strategic planning to climate change requires a general understanding of future climate and forest conditions. (2) Integrating climate change into a strategic planning model like Woodstock requires developing a method to link outputs from the climate-sensitive, process-based stand models to the strategic decision support models. (3) Testing and validating climate-adapted strategic planning using diverse silvicultural tools and linear programming depends on plausible climate projections and a functional method to link outputs from climate-sensitive, process-based stand models to strategic decision support models.

Table 5.1. Connections between discussed themes and research chapters.

Theme	Research Chapter 1	Research Chapter 2	Research Chapter 3
Species Composition	Declining boreal species; temperate deciduous species rise.	Validates shifts using models; guides planning.	Landscape-level dynamics; testing adaptive strategies.
Productivity Decline	Stress on conifers; reduced growth and resilience.	Yield tables show consistent declines.	Operable wood volume declines; economic impacts.
Economic Challenges	Not directly addressed.	Incorporates revenue indicators in models. They declined.	Stumpage revenue and PV changes under climate scenarios.
Disturbance considerations	Notes vulnerability but doesn't model impacts.	Not explicitly addressed.	Environmental considerations indicators for natural disturbances (fire, drought) and species richness.
Management Practices	Highlights need for adaptive strategies.	Promotes strategic integration of climate effects.	Exploring partial-cutting relevance with clear-cutting under climate change.

5.1.1. Linking species composition shifts to strategic forest planning

The shifting composition of the Acadian forest, as highlighted in research chapter 1, provides a foundational understanding of the ecological dynamics under climate change across and beyond the studied landscape. This synthesis was essential, as information on these dynamics is often scattered across the literature, and climate projection models are complex to synthesize into actionable insights for specific regions. Albert et al. (2023) demonstrated how increasing temperatures and changing water balances are driving a transition from boreal softwoods, such as balsam fir and white spruce, to temperate hardwoods, such as red maple and yellow birch, at the stand level. These ecological shifts highlight the urgent need to incorporate adaptive strategic forest planning tools to maintain

forest resilience and productivity. Strategies such as assisted migration, thinning, partial cuts, and clear-cutting can optimize growth rates and intervention timings, both critical determinants of wood supply as climate change alters forest dynamics.

The PICUS stand model was selected to bridge the projected effects of climate change from the stand level to the landscape level because of its process-based and climate capable nature. This model, previously calibrated for the Acadian forest region (Taylor et al. 2017), has been identified as one of the most effective tools used in scientific research for the study area (Metsaranta et al. 2024). Stand-level projections generated by PICUS were integrated into climate-sensitive yield tables and transition rules in research chapter 2. These yield tables were then incorporated into the strategic planning model Woodstock, as detailed by Albert et al. (2024). The results correspond closely to shifts predicted at other management scales by the studies reviewed in research chapter 1.

The integration of climate-sensitive yield tables and transition rules into the strategic forest planning model Woodstock required at least four land classification schemes. The landscape-level modeling results revealed significant reductions in merchantable wood volume of up to 50 % in clearcut-only scenarios under climate change. In all cases, climate change scenarios produced less wood and ultimately reduced the annual allowable cut. Such shifts in available volume and other forest conditions would not have been identified under baseline-only considerations. The findings in Albert et al. (2025) clearly demonstrate that integrating climate change into yield tables and transition rules enables strategic landscape plans to account for climate change impacts effectively and reduce the risk of fibre shortages. These results corroborate findings from other landscape-level studies across North America where available volume was decreased in all climates forcing

scenarios, increasing fibre shortage risks (Daniel et al. 2017; Brecka et al. 2020). Climate-adapted landscape management plans developed using the methodology from this thesis aim to inform forest managers of potential future risks associated with their strategies and identify proactive actions to reduce those risks.

5.1.2. Productivity declines and economic implications

Research conducted in this study and across North America consistently highlights a troubling decline in landscape-level productivity under climate change scenarios. In the Acadian forest, the underperformance of boreal conifers under warmer conditions is driving projected declines in available wood, while gains in temperate deciduous species are unable to fully compensate. These findings were explored in research chapters 2 and 3 and corroborate the findings in other studies aimed at predicting wood supply under climate change (Molina et al. 2021; Ameray et al. 2023; McMonagle et al. 2024). However, the decline in operable volume varies depending on management strategies: it decreases from up to 50 % using the "harvest older stands first" priority rule to only 10% when optimization selects the most appropriate harvest action between partial harvest and clear-cutting, alongside optimal treatment timing to maximize revenue. Overall, the annual volume harvested declined by 13 % under RCP8.5 when compared to the baseline using the older stand first priority compared to 9 % decline when optimizing stumpage revenue using partial-cutting and clear-cutting as available treatments.

The main findings in research chapter 3 reveal that, contrary to expectations, there was no significant shift from clear-cutting to partial-retention harvest. However, partial harvesting helped maintain fiber supply under climate change when combined with clear-

cutting when maximizing stumpage revenue, as reflected in the yield curves and transition rules. Given the shift in species composition toward hardwoods observed throughout this thesis, deciduous species prices are likely to decline. Such market dynamics could push future projections to favor retention harvests, taking advantage of enhanced conifer regeneration under moderate climate warming. By strategically timing harvests, the Woodstock model optimized revenue by targeting vulnerable stands early and retaining stands dominated by species with high economic value, such as balsam fir and spruces, using partial cutting to maintain and leverage the "blocking effect." This effect delayed the transition toward temperate species like red maple, yellow birch, and white pine, which increased in recruitment and growth performance over time under warmer climates but generated lower revenues.

Economically, the implications of these results are significant. All economic indicators in research chapters 2 and 3, including stumpage revenue and present value, show lower levels under climate change scenarios compared to the baseline aligning with other landscape-level study results (e.i., Lantz et al. 2022; McMonagle et al. 2024). This decrease is primarily attributed to shifts toward less profitable deciduous species and reduced harvest volumes due to a decline in per-hectare productivity across the landscape. The shift in species composition is also expected to challenge future supply chains, particularly for conifer mills, as the harvested product mix shifts from conifer to deciduous dominated. This transition necessitates additional investments, reducing sector profitability during the adaptation period. However, assisted migration and conifer plantations will certainly continue to play a role in delaying and mitigating the deciduous species occupation of the landscape, but further investigation is required.

The strategic planning modeled in this thesis maximized stumpage revenue by prioritizing stumpage prices, which are higher for conifer species. Consequently, the resulting management schedules already reflect the maximum feasible conifer harvest volumes given what the climate-sensitive yield tables and transition rules have implemented.

5.1.3. Ecological and management trade-offs

The research presented in this thesis highlights the potential risks that climate change poses toward sustainable forest management. The research chapter 3 analysis of harvesting practices revealed only modest shifts toward partial harvest treatments, despite their documented ecological benefits, such as maintaining soil moisture, supporting biodiversity, and providing more stable microclimatic conditions (Bose et al. 2023). This finding reflects a fundamental gap between the theoretical benefits of partial harvests and their practical implementation when economic considerations dominate.

Ecological insights from research chapter 1 provide context for understanding management trade-offs. For example, the vulnerability of boreal species to warming highlights the need for proactive strategies that promote underrepresented and resilient species like yellow birch (Nagel et al. 2017). Similarly, adaptive management practices such as retention harvest systems, recommended in research chapter 1, demonstrate potential for balancing timber production with ecological sustainability. However, the limited adoption of these strategies observed in research chapter 3 suggests that economic feasibility often constrain their application.

The integration of climate-sensitive strategic forest planning as presented in this thesis provides forest managers the opportunity to evaluate multiple possible future scenarios. By simulating how various climate projections and management strategies may influence the forested landscape, managers can better understand the trade-offs involved in decisions made today. This foresight enables informed choices that minimize long-term negative impacts on the forest while maintaining sustainable forest management practices. For example, decisions about whether to prioritize short-term economic gains through clear-cutting or to invest in ecologically beneficial practices like partial retention harvesting can be guided by scenario-based evaluations of resilience and productivity outcomes under different climatic conditions.

5.1.5. Concluding remark

This thesis offers a comprehensive investigation into the multifaceted challenges posed by climate change to forest management in the Acadian forest region, advancing the integration of adaptive strategies into strategic forest planning. By leveraging the latest forest inventory collected using cutting-edge technologies and climate projections from the Ouranos Climate Center, this research developed and tested an innovative approach that incorporates climate-sensitive yield and transition tables into a new strategic planning method.

The first research chapter addressed the dispersed literature on climate impacts by consolidating projections of key climatic variables, including temperature, precipitation, growing degree days, and moisture indices, into a single paper for New Brunswick. This synthesis not only set the stage for the subsequent research chapters but also highlighted

critical risks to forest dynamics and underscored the importance of resilience-focused interventions. Research chapter 2 expanded on these findings by operationalizing a new climate-adaptive approach to forest management planning. Using the PICUS stand-level model, dynamic yield tables and transition rules sensitive to climate projections were developed and integrated into the Woodstock planning system, providing a robust decision-making tool. This approach differed and from the past modifier approach by integrating climate change in every intricate detail of stand dynamics (regeneration, growth, and mortality). The results showcased the potential of this approach to address the climate change challenge on forest planning, emphasizing the anticipated decline in boreal species and wood supply under climate warming scenarios at the landscape scale. Finally, research chapter 3 elevated these innovations further by evaluating the trade-offs and impacts of various harvesting strategies under climate scenarios and quantifying the economic and ecological implications of different treatments and their impacts on landscape risks to environmental stressors.

Together, these three research chapters contribute to advancing strategic forest planning by equipping managers with tools to evaluate and mitigate climate-related risks. This research underscores the critical importance of adaptive management practices that not only respond to immediate challenges but also anticipate and prepare for future uncertainties, ensuring sustainable forest ecosystems and wood supply.

5.2. Limitations

Some limitations apply to this thesis and the results it presents should be interpreted with judgment. Below is a list of limitations that might have an influence on the results.

(1) The use of an ensemble of climate models (24 in this study) to predict future climate variables under climate change (research chapter 1) fails to accurately capture rare or extreme events, as these are normalized within the ensemble mean. Furthermore, the coarse spatial resolution of climate models necessitated downscaling, which does not adequately capture local-scale phenomena such as microclimates or regional weather patterns.

(2) The PICUS model relies on accurate climate data, soil moisture and fertility, and initial stand parameters as its main inputs. In this study, average soil moisture and fertility for New Brunswick were used (research chapters 2 and 3). These parameters, which likely have a significant impact on tree species performance under climate change, were not specifically studied in this thesis. Additionally, some species, such as red spruce and American beech, performed exceptionally well under baseline conditions in some cases, which did not align with observed performance. This indicates the need for further calibration of the model. For instance, American beech was excluded from simulations because PICUS cannot accurately simulate the effects of beech bark disease.

(3) Only the climate change effect on growth and species composition was studied in this thesis, natural disturbances were not considered.

(4) Between climate projections, stand level simulations, and landscape level simulations, uncertainty is building up, projections are made based on many plausible assumptions, however, a different set of plausible assumptions could be used to project different results.

(5) The use of only four initial age bins to account for the dynamic nature of yield tables under changing climates (research chapters 2 and 3) introduced an error margin between the observed forest inventory and the initial inventory of the strategic model.

(6) The use of only three transition periods (research chapters 2 and 3) limited the accuracy of predictions regarding forest composition post-harvest.

(7) The novel method presented in research chapter 2 was tested using a strategic harvest intensity of 1% of the landscape per year. Higher or lower harvest intensities may yield different outcomes that were not explored in this study. Since we applied an area-based control method, future work should test volume-based control to evaluate its impact on results.

(8) In research chapter 3, the assumption was made that the product prices would remain static across the planning horizon which impacted the resulting objective function (maximising stumpage revenue). Markets are continuously evolving so are the forested landscapes, a change in supply will impact prices which was not considered in this research.

(9) To evaluate the risks posed by climate change on wood supply and financial outcomes, and to assess the impacts of climate change on harvesting treatments, an objective function that maximizes stumpage revenue was used in Woodstock (research chapter 3). However, different objective functions could lead to varying results, which were not analyzed in this thesis.

5.2.1. Limitations of PICUS simulations

There is a critical caveat for strategic planning: the variability among growth models under baseline conditions often matches, or even exceeds, the magnitude of climate-driven declines projected by the same process-based model (Figure 5.1). For instance, in the BFMX stand type (the most abundant at Gagetown) at age 40, PICUS forecasts a merchantable volume of 149 $m^3 \cdot ha^{-1}$, whereas the Open Stand Model (OSM; available at : https://forusresearch.com/downloads/osm/index.html) and the empirically based Nova Scotia Growth & Yield Model (NSGYM; available at : https://novascotia.ca/natr/forestry/programs/timberman/growthyield.asp) predict only 129 $m^3 \cdot ha^{-1}$ and 125 $m^3 \cdot ha^{-1}$, respectively. This 20–24 $m^3 \cdot ha^{-1}$ discrepancy across models is comparable to the 42 $m^3 \cdot ha^{-1}$ mean reduction that PICUS projects under RCP8.5 at the same age across all stands.

Moreover, this baseline discrepancy varies widely among stand types, from –9 $m^3 \cdot ha^{-1}$ up to +306 $m^3 \cdot ha^{-1}$ (WPSW) when comparing PICUS to OSM, and from 0 to +292 $m^3 \cdot ha^{-1}$ for PICUS versus NSGYM (Figure 5.1). Averaged across all stand types and ages, OSM volumes are 38 $m^3 \cdot ha^{-1}$ lower than PICUS, and NSGYM volumes are 24 $m^3 \cdot ha^{-1}$ lower. In some cases, the inter-model spread under baseline alone exceeds the worst-case climate impact, underscoring that structural uncertainty in growth algorithms can overshadow the climate signal.

Certain PICUS outputs also strain empirical plausibility: some age-35 volumes exceed 200 $m^3 \cdot ha^{-1}$, which implies average annual increments > 6 $m^3 \cdot ha^{-1} \cdot yr^{-1}$, well above the long-term field observations of ~ 2 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in the Acadian region (Figure 5.1; Penner et al. 2006; Arseneault et al. 2011).

Each model carries its own limitations. OSM's reliance on historical yield–growth relationships assume climate stationarity, risking misspecification under novel climates. NSGYM, calibrated on monospecific trial plots, neither captures mixed-stand interactions nor explicitly simulates drought or heat stress beyond the range of its calibration data. Consequently, all three models show increasing uncertainty when projecting a warmer future. Despite differences among the OSM, NSGYM, and PICUS stand models, the main interest was to quantify the differences between climate scenarios rather than explain the specific shape of each projections.

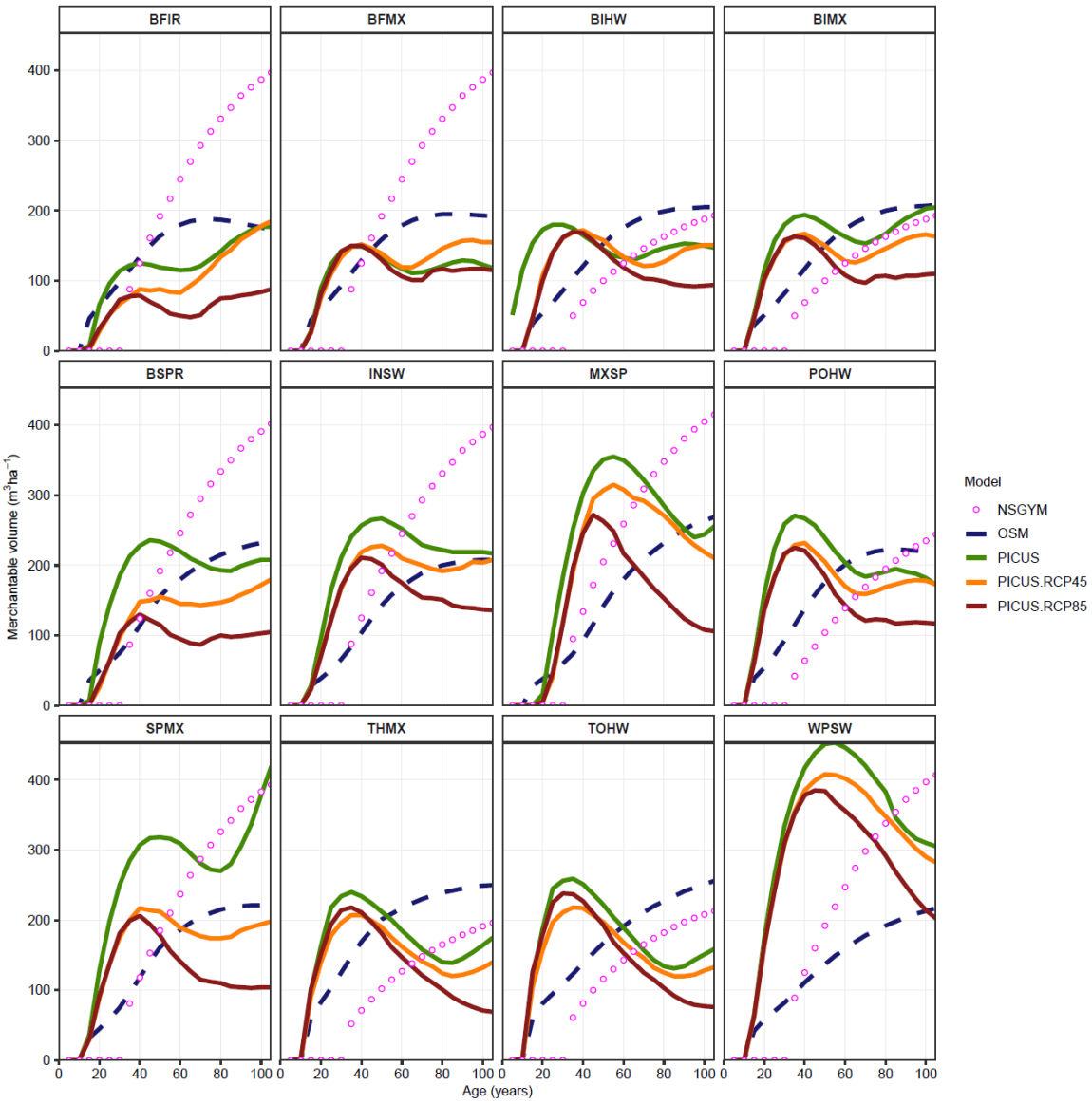


Figure 5.1. Simulated merchantable volume over time for 12 stand types using PICUS, the Open Stand Model (OSM), and the Nova Scotia Growth and Yield Model (NSGYM). Note: NSGYM can only model monospecific stands; therefore, only the dominant species within each stand type was used.

5.3. Future research

Considering the findings of this research and the limitations identified, numerous avenues for future exploration emerge. These opportunities, listed bellow, can build upon the current work to address unanswered questions and refine methodologies.

(1) As natural disturbances evolve alongside the changing climate, they must be explicitly integrated into strategic planning frameworks to fully account for climate adaptation. This is particularly critical given the increasing inadequacy of human efforts to suppress such disturbances effectively.

(2) Species composition is expected to shift because of climate change, which will increasingly impact mills that process roundwood, further studies should further quantify the risk and the potential impacts for the wood transformation industries.

(3) To continue the adaptation of the forest planning sector to climate change, the impact of climate change on the spatial management plan resulting from the climate sensitive strategic plan, including the blocking process, should be explored.

(4) Future research should focus on quantifying the uncertainties arising from each step of the strategic planning process. Understanding the key drivers of these uncertainties is important to developing methods that minimize them and enhance the robustness of planning outcomes.

(5) With a diverse range of treatment actions and the development of resilience indicators at the landscape level, optimization efforts should aim to maximize landscape resilience. Further, research is needed to determine the specific treatments required under pre-defined conditions to achieve these resilience goals.

(6) To promote transparency, reproducibility, and future collaboration, all models and input data used in this study have been deposited in the UNB Dataverse Repository: https://doi.org/10.25545/ZHZJHV. This open access allows researchers and practitioners to explore the modeling framework, test alternative assumptions, or adapt the approach to other regions and forest systems.

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Publications

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