Quote

"Is it possible for a man to move the earth? Yes; but he must first find out another earth to stand upon."

Jeromy Bentham (1748-1832), An Introduction to the Principles of Morals and Legislation

ECONOMIC IMPACT OF CLIMATE CHANGE ALTERING THE STRUCTURE OF

NEW BRUNSWICK'S AND QUÉBEC'S FOREST:

A PICUS-LANDIS CGE ANALYSIS

By

Galen Robert James McMonagle

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Supervisor: Van A. Lantz, PhD, Forestry and Environmental Management

Examining Board: Graham Forbes, PhD, Forestry and Environmental Management, Chair

Fanrui Meng, PhD, Forestry and Environment Management

Herbert Emery, PhD, Political Science

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Dean of Graduate Studies

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Abstract

Climate change and harvesting is expected to alter the structure of forests in Canada, as individual tree species will react differently to regional changes in environmental characteristics. While numerous studies have employed models to assess the ecological and/or economic impacts of such changes on forests, there is need to further refine such analyses. This thesis contributes to the literature by coupling an ecological (PICUS-LANDIS II) modeling framework with an economic (CGE) model to better account for the economic impact associated with changes in forest stand and landscape-level dynamics. To demonstrate the contributions, this thesis considers two case-study regions - New Brunswick, and Québec. The thesis finds that a reduction in softwood supply due to either climate change or harvesting activities results in an economic loss at both the macro and sectoral level. The negative impact on softwood species outweighs the economic benefit associated with climate change positively impacting hardwood species.

Dedication

To my late grandmother Alberta (*Bertie)* Louise Hunter, I wish you were here to see how far we have come. When you originally left Atlantic Canada segregated school were still in existence, and now look where we are. Rest in Peace.

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First and foremost, thank you to my supervisor Dr. Van Lantz. Without you this thesis would not be possible. Your patience and determination provided me with the hope and motivation needed to finish this thesis. Working with you has been an amazing experience and one that I will always cherish.

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List of Acronyms

AAC	Annual Allowable Cut
ACC	Accommodation & food services
ADMIN	Administration
CGE	Computable General Equilibrium
CONST	Construction
CP-MANUF	Converted paper product manufacturing
CROP	Crop & animal production
EDUC	Education
ENT	Entertainment
FIN	Finance
FISH	Fishing hunting & trapping
GAMS	General algebraic Modeling Solver
GDP	Gross Domestic Production
HEALTH	Health care
H-FOR	Hardwood forestry and logging
INFO	Information
IO	Input-output
OG&S	Other goods & services
OILGAS	Mining quarrying, oil, and gas extraction (OILGAS)
OTH-MANUF	Other Manufacturing
OW-MANUF	Other wood product manufacturing
PR-MANUF	Printing and related activities
PROF	Professional
PUP-MANUF	Pulp paper and carboard mills
RET	Retail trade
RoW	Rest of World
SAM	Social Accounting Matrix

SAW-MANUF	Sawmills and wood preservation
SBW	Spruce budworm (*Choristoneura fumiferana* [Clem.])
SEEA	Social Environmental and Economic Accounts
S-FOR	Softwood forestry and logging
SUPP	Support activities for agriculture & forestry
TRADES	Wholesale trade
TRANSP	Transportation
UTL	Utilities
VEN-MANUF	Veneer plywood manufacturing

Chapter 1 General Introduction

1.1 Introduction

Forests cover more than 75% of Canada's landmass (362 million hectares) and account for 9% of the world's forest (Resources Canada, 2022). The abundance of forests has allowed Canada to develop one of the world's largest forestry and logging sectors, supplying 158, 951,129 million meters ^{3} of softwood and 56,361,615 million meters^{3} of hardwood in 2020 (Canadian Council of Forest Ministers, 2022). Not only is the forestry sector reliant on the quantity of wood supplied, but it is also dependent on its composition - as hardwood and softwood have varying degrees of economic value and are uniquely used as required inputs for various wood related manufacturing sectors[1] (Resources Canada, 2022).

The high dependence on quantity and composition of wood supply makes Canada's forestry and wood-related manufacturing sectors at risk of being negatively impacted by climate change. Climate change is expected to have numerous impacts on the forest landscape, as it will alter the regional temperature, precipitation, and the severity and likelihood of extreme weather events (i.e., droughts, forest fires, and windfall). These climate-induced changes are expected to impact individual tree species differently with cold-adapted softwood species experiencing a decrease in both abundance and yield across Canada (Ashraf et al., 2015; Boulanger et al., 2017; Brecka et al., 2018, 2020; Taylor et al., 2017). Meanwhile, warm-adapted hardwood species

[1] Wood related manufacturing sectors include sawmill and wood preservation, veneer plywood manufacturing, pulp paper and cardboard mills, converted paper product manufacturing, printing and related activities, and other wood product manufacturing. Further explanation of wood related manufacturing sectors can be found in Chapter 2 and 3.

such as red maple may experience an increase in abundance and yields under climate change (Ashraf et al., 2015; Boulanger et al., 2017; Brecka et al., 2018, 2020; Taylor et al., 2017). This is due to red maple's physiology allowing them to adapt to a warmer climate, in doing so they will only experience a minor decrease in overall fitness under climate change (Vaughn et al., 2021). This minor decrease in fitness is not enough to prevent a northern expansion in the range of warm-adapted tree species as areas that were once to cold for them begin to warm (Sittaro et al., 2017). Furthermore, the minor decrease in fitness of warm-adapted species in conjunction with a significant decrease in fitness of cold-adapted tree species (Vaughn et al., 2021) will result in a shift in forest structure (Boulanger et al., 2017), as warm adapted hardwood species outcompete currently dominant cold-adapted species. These changes in forest structure will alter various forest services including wildlife habitat (St-Laurent et al., 2022; Tremblay et al., 2018) and wood supply (Brecka et al., 2018, 2020).

Recent studies (Corbett et al., 2016; Karttunen et al., 2018; Liu et al., 2019; Ochuodho et al., 2012; Ochuodho & Lantz, 2014; Phimmavong & Keenan, 2020) have tried to quantify the economic impact of a change in wood supply by using computable general equilibrium (CGE) models. These studies have revealed the potential for significant economic impacts in the forestry and logging sector, as well as changes in key macro-economic variables including, gross domestic production (GDP), household income, and consumer welfare from changes in wood supply . While these studies provide a general understanding of potential impacts, they do so by possibly oversimplifying the interactions that are occurring in the forest landscape – since they

do not model these dynamics but rather rely on previous studies and/or expert opinion. This oversimplification is further highlighted by the studies using an aggregate wood supply input in their CGE models rather than distinguishing between hardwood and softwood supply which, as described above, may vary significantly in response to climate change.

Hence, there is a need to refine recent CGE models and join them with current forest landscape models to create a robust framework that simulates changes in the forest landscape and the associated economic impacts. To examine the extent to which a climate-induced change in forest structure will impact the economy, this thesis will focus on two case study regions: New Brunswick and Québec.

The rest of this chapter is formatted as followed: Section 1.2 explores past studies and provides the necessary background information on the two case study regions; Section 1.3 highlights the critical research gaps and how the gaps are impacting current research and climate mitigation strategies; Section 1.4 presents the objectives and framework for this thesis and explains how it will contribute to current literature; and Section 1.5 concludes this chapter by providing a brief introduction for the following three chapters.

1.2 Background

The forests in New Brunswick and Québec play a significant role in their respective provincial landscapes, as each forest contains cultural, ecological, and economic significance to the respective province. In Québec, the forest covers 50% of

the provincial landmass (90 million hectares, Government of Québec, 2016), with the forestry sector harvesting 22 million m^3 of softwood, and 6 million m^3 of hardwood annually (CCFM, 2020). This has led forestry and wood-related sectors to contribute $6.8 billion dollars worth of GDP to the economy (Statistics Canada, 2022) with the forestry and locking sector alone employing 10,000 individuals (Statistics Canada, 2021). This is the second largest forestry and wood-related sector by value in Canada, only behind British Columbia (Statistics Canada, 2022).

Québec's forest covers two separate forest regions – the Boreal Forest Region and the Great Lakes-St Lawrence Forest Region (Figure 1.1). The Boreal Forest Region is the largest of the two regions and is found throughout Québec with the exception of the southmost part of the province (Rowe, 1972). The forest region is bordered by the Acadian Forest Region in the east, and the Great Lake-St Lawrence's Forest region in the south (Rowe, 1972). The Boreal Forest Region is characterized by the dominance of cold-adapted tree species such as balsam fir (*Abies balsamea*), tamarack (*Larix laricina*), red pine (*Pinus resionosa*), white birch (*Betula papyrifera*), white spruce (*Picea glauca*), black spruce (*Picea mariana*), and jack pine (*Pinus banksiana*, Rowe, 1972).

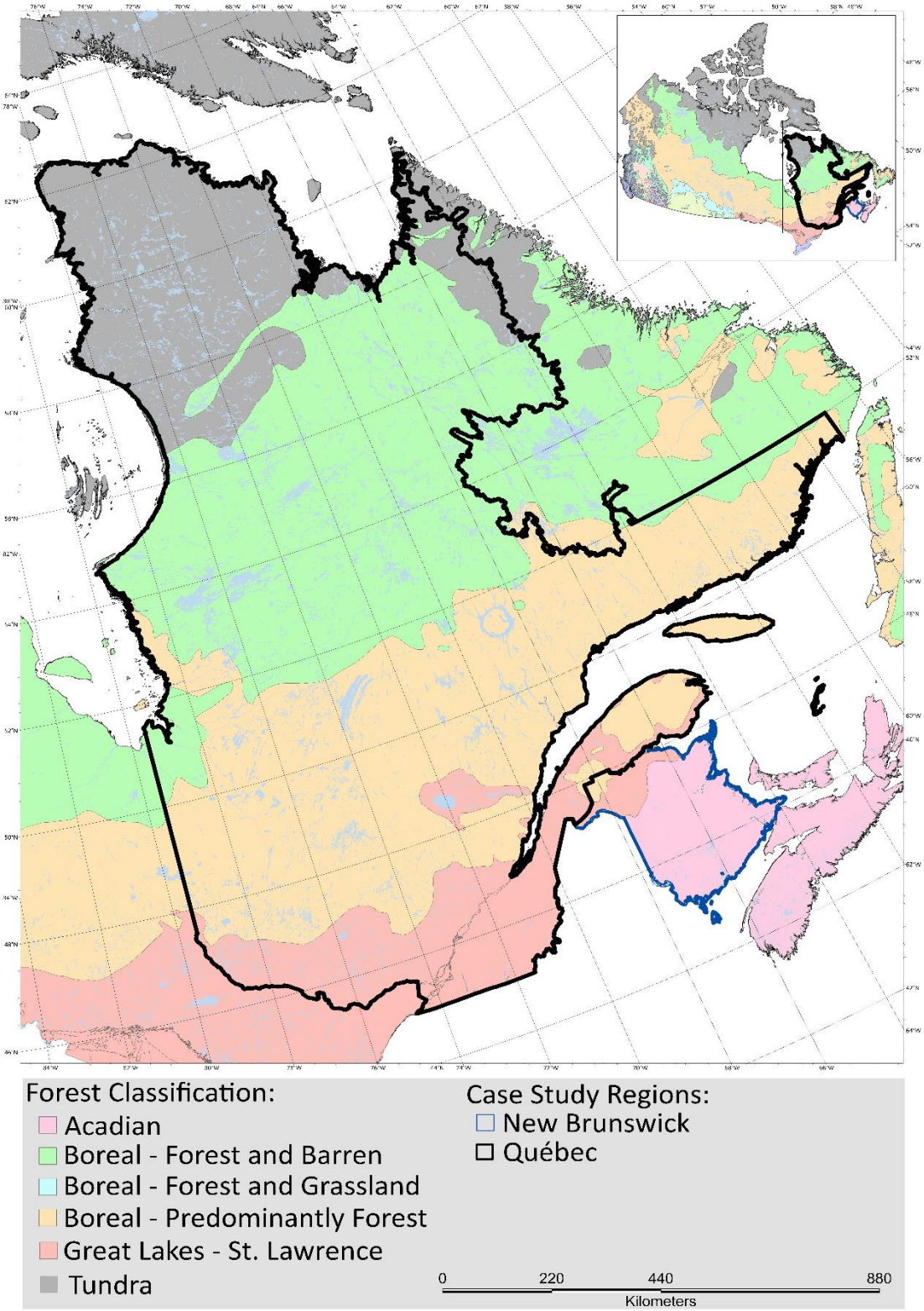

Figure 1.1 Rowe's Forest classification (Rowe, 1972) in the case study regions of New Brunswick and Quebec

The Great Lakes-St Lawrence Forest Region is located in the southern part of Quebec, along the St Lawrences River (Rowe, 1972). The environment caters to warm adapted tree species, with eastern white cedar (*Thuja occidentialis*), eastern hemlock (*Tsuga canadensis*), red pine, red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), and northern red oak (*Quercus rubra)* all being dominant species (Rowe, 1972). There is no clear boundary between the two forest regions and as such the transition zone consists of a mix of warm-adapted species, and cold-adapted species.

Meanwhile, New Brunswick's forests make up approximately 80% (6 million hectares) of the provincial landmass (Government of New Brunswick, 2015). New Brunswick's forest is part of the Acadian Forest Region (Figure 1.1) which stretches across both Atlantic Canada (New Brunswick and Nova Scotia) and Northeastern US States (Maine and New Hampshire). The forest is bounded by the Atlantic Ocean in the East and the Boreal Forest in the south and west (Rowe, 1972). The Acadian forests have a unique mixture of cold-adapted softwood species (e.g., balsam, black spruce, and red pine) and warm-adapted tree species (e.g., sugar maple, red maple, and yellow birch (Baldwin et al., 2019; Rowe, 1972)).

New Brunswick's forestry sector harvests 6 million m^3 of softwood and 3 million m^3 of hardwood annually (CCFM, 2020), which allows the forestry and wood related sectors to contribute $1.3 billion worth of GDP to the provincial economy (Statistics Canada, 2020). Furthermore, the forestry and logging sector employs over 3,200 individuals (Natural Resources Canada, 2020). New Brunswick's forestry and wood

sectors are the largest in Canada, by the proportion of provincial GDP, as it makes up roughly 5% of the provincial economy (Statistics Canada, 2022).

Due to the economic significance of forestry around the world, there are numerous studies (Perez-Garcia et al., 1997, 2002; Sohngen et al., 2001; Sohngen & Sedjo, 2005) that examine how a change in wood supply will impact the economy. These studies have historically used a wide range of economic models and tools to assess the economic impact of a change in wood supply. Recently, however, there has been a shift towards the use of CGE models to examine how an economy will react to a change in wood supply (Boccanfuso et al., 2018; Corbett et al., 2016; Karttunen et al., 2018; Liu et al., 2019; Malahayati & Masui, 2019; Ochuodho et al., 2012; Ochuodho & Lantz, 2014; Phimmavong & Keenan, 2020). CGE models were first described by Dervis et al. (1982), and were created to address the limitations of input-output models. CGE models use a system of equations based on neo-classical economic theory to simulate how an economy will react to a market shock, with shocks taking several forms including changes in taxes, prices, output, and factors of production. Recent forestry-related CGE studies incorporate wood supply as a factor of production by using a 3-factor (labour, capital, and wood supply) production function based on Lofgren et al. (2002).

Researchers have used this 3-factor production function to try to quantify the economic impact associated with climate change impacting the regional wood supply in both of the case-study regions considered in this thesis (Boccanfuso et al., 2018; Ochuodho et al., 2012; Ochuodho & Lantz, 2014). Ochuodho and Lantz (2014) used a

single regional CGE model to determine that cumulative (4% discount rate) GDP could increase by 0.03% to 0.23% and 0.061% to 0.098% for New Brunswick and Québec, respectively, between 2006 and 2051 depending on the severity of climate change. Meanwhile, Boccanfuso et al. (2018) also used a single regional CGE model to show that a climate-induced change in wood supply could result in a 0.12% decrease in Québec's GDP by 2058. Furthermore, both studies found a significant reduction in the value of output from the forestry and logging sector.

Although these studies provided a broad insight into how the economies in New Brunswick and Québec will react to a change in the quantity of wood supply, they may oversimplify the impact climate change will have on the forest. This is in part due to the methodology they use to determine the impact climate change will have on wood supply. Specifically, these studies rely on peer-reviewed papers (e.g., Flannigan et al., 2005; Lemprière et al., 2008; Yamasaki et al., 2012) and expert opinion to determine the impacts. For instance, Ochuodho and Lantz (2014), estimates that forest productivity will change between -1.0% and -7.2% in New Brunswick and +2.6% to -6.5% in Québec by 2051. These relatively large ranges of possible impacts are partly a result of using a range of historical peer-reviewed papers and/or expert opinion.

The possible oversimplification of climate change impacts on wood supply in past economic studies becomes more evident when examining recent forestry-related studies that simulate the impact climate change will have on forest-stand and forest-landscape dynamics and the associated changes in forest structure (Boulanger et al., 2017, 2018; Boulanger & Puigdevall, 2021) and forest services (Brecka et al., 2020;

Moreau et al., 2022; St-Laurent et al., 2022; Tremblay et al., 2018). These studies are able to simulate forest-stand and forest-landscape dynamics under a variety of anthropogenic and non-anthropogenic disturbances by using the PICUS-LANDIS-II framework (hereafter PICUS-LANDIS). PICUS-LANDIS is a spatially intensive framework that is made up of two separate models, PICUS and LANDIS-II.

PICUS (V1.5; Lexer & Hönninger, 2001) is a forest gap model that simulates the growth, death, and germination of individualspecies within a forest patch. These patches can be placed beside each other to model a forest stand. The outputs from PICUS are used to calibrate the dynamic component of LANDIS-II. LANDIS-II is a spatial intensive forest landscape model that simulates forest succession at a landscape level while accounting for various anthropogenic and non-anthropogenic disturbances (Scheller et al., 2007).

Recently, Brecka et al. (2020) used PICUS-LANDIS to examine the extent to which climate change will impact regional wood supply across Canada. The study highlights a significant decrease in economically important cold-adapted softwood species, with total biomass harvested decrease by as much to 40% by 2200 in the boreal shield east. Furthermore, the study suggests that reducing the harvesting rates may improve the long-term economic viability of the forestry sector. It should be noted that the study does not conduct a formal economic analysis, but instead draws this conclusion based on the long-term changes in quantity and composition of the wood supply.

1.3 Critical research gap

As previously mentioned, numerous CGE studies examine the economic impact associated with climate change and climate mitigations strategies impacting wood supply (Corbett et al., 2016; Karttunen et al., 2018; Liu et al., 2019; Ochuodho et al., 2012, 2016; Ochuodho & Lantz, 2014; Phimmavong & Keenan, 2020). However, these studies tend to oversimply the extent to which climate change alters the forest landscape, as the studies rely on peer-reviewed papers and expert opinion to determine the change in wood supply. This is further highlighted by these economic studies not distinguishing between hardwood and softwood supply inputs. In doing so these studies have not been able to examine how a change in the composition of wood supply will impact the economy.

Hence, there is a need for an enhanced CGE model that can simulate climate-induced changes in both the quantity and composition of wood supply. Once developed, such an enhanced CGE model could be joined with PICUS-LANDIS, to create a PICUS-LANDIS-CGE framework. This framework would improve the robustness of studies that examine the economic impact of a climate-induced change in forest structure, as PICUS-LANDIS will simulate the change in quantity and composition of wood supply, while the CGE model will simulate the economic impacts. With such a framework, economics researchers would no longer need to rely on peer-reviewed papers and expert opinion to estimate the manner in which climate change will impact wood supply. Furthermore, a PICUS-LANDIS-CGE framework would allow for a better

understanding of how forest management strategies affect both the forest ecosystem and the economy.

1.4 Research objectives

The main objectives of this thesis are to: (i) develop an enhanced economic and ecological modeling framework to assess the economic impacts of climate change in forests; (ii) implement the framework in the case-study regions of New Brunswick and Quebec; and (iii) consider the interactions between climate change and timber harvesting rates and how they impact forest dynamics, wood supplies and the economy.

There are several steps involved in developing the above-described framework. First, a standard CGE model will be enhanced by disaggregating the forestry and logging sector into a hardwood forestry and logging sector (H-FOR) and a softwood forestry and logging sector (S-FOR) within a social accounting matrix (SAM). Creating a SAM that contains both H-FOR and S-FOR is the first step in creating a CGE model that can distinguish between hardwood and softwood supply, as a SAM is required to parametrize the CGE model to an economy.

Second, a four-factor CGE model will be defined that includes hardwood and softwood timber supply inputs (in addition to labour and capital inputs). As previously mentioned, past CGE studies focusing on the forest sector aggregate hardwood and softwood supplies into a single wood supply input. In doing so, these studies are unable to properly simulate how a change in composition of wood supply will impact the regional economy.

Third, the enhanced CGE model will be joined with PICUS-LANDIS[2] to create the PICUS-LANDIS-CGE model framework. In doing so PICUS-LANDIS will be able to simulate how wood supplies will change under various climate change scenarios, while the CGE model will be able to estimate the economic impact of such changes.

1.5 Conclusion

The rest of the thesis is written in article format, with Chapters 2 and 3 being standalone articles. Each article addresses at least one of the research objectives mentioned above.

Chapter 2 establishes the methodology used to disaggregate the SAM, as well as defining the four factor CGE model that is used within the PICUS-LANDIS–CGE framework. It applies the framework to the case study region of New Brunswick, with the purpose of examining how the composition of New Brunswick's forests will change under four different climate change scenarios and the associated short-term and long-term impact it will have on timber supplies and the economy. The purpose of this chapter is to both establish the framework as well as provide valuable insight for policymakers whose goals are to understand the impacts of climate change on the provincial forest, the forest sector and economy.

[2] PICUS-LANDIS has previously been calibrated to Eastern Canada (Brecka et al., 2020; Boulanger et al., 2017; Boulanger & Puigdevall, 2021). As such the calibration process of PICUS-LANDIS is outside of the scope of this thesis.

Chapter 3 builds on the previous chapter by applying the PICUS-LANDIS–CGE framework to the case study region of Québec and examining the economic viability of the forestry sector and provincial economy with climate change and harvesting interactions. In doing so this chapter tests the hypothesis that reducing the AAC will increase the long-term economic viability of the forest sector and provincial economy by improving the resilience of the forest to climate change.

Chapter 4 concludes this thesis by highlighting the significance of the findings from Chapters 2 and 3, summarizing limitations of the developed methodology, and indicating directions for future research.

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Chapter 2 Economic impacts of climate change on forests: a PICUS-LANDIS-CGE modeling approach

2.1 Abstract

Climate change is expected to alter both forest stand- and landscape-level dynamics through a change in temperature, precipitation, drought, fire, and other such regimes. While numerous studies have employed models to assess the ecological and/or economic impacts of such changes on forests throughout the world, there is need to further refine such analyses. In this paper, we contribute to this literature by coupling an ecological (PICUS-LANDIS II) modeling framework with an economic (CGE) model to better account for the economic impact associated with climate-induced impacts on stand and landscape-level structure and composition dynamics. Applying this framework to a case-study region of New Brunswick, Canada, we estimate that climate change will reduce softwood supply by 16-73% and hardwood supply in the range of -2% to +4% by 2150, depending on scenario. The change in both quantity and composition of wood supply is estimated to reduce the value of the softwood and hardwood forestry and logging sector output by up to 51% and 17%, respectively, by 2150. This will, in turn, have a negative impact on the value of wood-related manufacturing within the province, with output in some sectors decreasing up to 54%. These sector-level impacts may lead to a 0.08-0.88% reduction in annual GDP by 2150. The methodological advances established in this study can be used to better inform future forest management and economic plans that aim to lessen both the ecological and economic impact of climate change.

2.2 Introduction

New Brunswick's forests are a defining characteristic of the provincial landscape, covering approximately 80%, or 6 million hectares, of the provincial landmass (Government of New Brunswick, 2015). These forests make up part of eastern Canada's Acadian Forest Region (Rowe, 1972) which is a diverse ecological transition zone that links warm adapted temperate tree species from the south, such as sugar maple (*Acer saccharum)*, red maple (*Acer rubrum)*, and yellow birch (*Betula alleghaniensis)* with more northerly, cold-adapted boreal tree species such as balsam fir (*Abies balsamea)*, black spruce (*Picea maiana)*, and trembling aspen (*Populus tremuloides*) (Baldwin et al., 2019; Rowe, 1972).

New Brunswick's forest industry relies on the province's forests to provide a significant supply of hardwood and softwood which is used in a wide range of sectors throughout the economy, harvesting approximately 6 million m^3 of softwood and 3 million m^3 of hardwood annually (CCFM, 2020a). Correspondingly, the forestry and wood-related manufacturing sectors alone generate approximately $1.3 billion, or 5% of total gross domestic produce (GDP), in goods and services annually (Statistics Canada, 2020a) and employ over 10,000 individuals, or 3.5%, of the working population (Natural Resource Canada, 2020).

The province's high dependence on its forest reserves make it susceptible to climate change, as changes in temperature, precipitation, and extreme weather events are expected to negatively impact forest conditions (Taylor et al., 2017). Specifically, New Brunswick could experience an increase in temperature of 1.5 to 6°C (Lennmen et

al., 2018) before the end of the century, with changes in precipitation patterns and seasonal and yearly extremes becoming more common (Lines et al., 2008). Although the temperature increase will result in a longer growing season (Lines et al., 2008), other factors are expected to offset this benefit (Ollinger et al., 2008). For instance, a warmer climate is expected to have variable impacts on individual tree species, with cold-adapted boreal species (such as balsam fir and black spruce) experiencing a contraction of their southern range limit, and warm-adapted species will experience a northward shift in their abundance (Ashraf et al., 2015; Boulanger et al., 2017; Searls et al., 2021; Taylor et al., 2017). These modifications in tree physiology for both warm- and cold-adapted species will alter the competitive advantage of individual species within the forest and result in a change of forest composition – as once dominant softwood trees species begin to be outcompeted by warmer adapted hardwood tree species (Taylor et al., 2017, 2020). This change in forest composition will result in a decrease in abundance of economically important softwoods such as balsam fir and black spruce (Engie, 2018), which account for over 65% of wood harvested in the province (CCFM, 2020a). The change in species competitiveness will also likely result in an increase in abundance and biomass harvested of several hardwood species (Taylor et al., 2017), specifically red maple, a super-generalist species (Abrams, 1998), which has been shown to outperform softwood tree species in a warming climate (Vaughn et al., 2021).

Several studies have investigated the economic impacts of climate change on forests using various modeling approaches. For instance, some studies have coupled

ecological models with global timber market models to assess the economic impacts of climate change on forests and forest sectors throughout the world (e.g., Sohngen & Sedjo, 2005; Perez-Garcia et al. 2002, 1997; Sohngen et al., 2001). The ecological models used in these studies take the form of global terrestrial ecosystem/biosphere models (e.g., BIOME 3, Terrestrial Ecosystem Model) that estimate how vegetation and timber supply will change over time. These studies typically reveal significant timber supply and output losses for Canadian timber producers under climate change. However, these studies do not consider the larger macro-economic (or economy-wide) impacts of climate change on gross domestic product, household income and consumption, government expenditures, investment, or trade.

To address the need for macro-economic assessments of climate change on forests, a number of more recent studies have used computable general equilibrium (CGE) models (e.g., Boccanfuso et al., 2018; Lantz et al., 2022; Ochuodho et al., 2012, 2016; Ochuodho & Lantz, 2014). These studies often reveal significant macro-economic losses for Canadian regions from climate change. However, most of these studies generally rely on somewhat abstract wood supply scenarios drawn from previous literature. For instance Ochuodho et al. (2012) use estimates of future climate-induced changes to forest productivity, pest outbreaks, and fire regimes across Canadian provinces from published literature (i.e., Flannigan et al., 2005; Lemprière et al., 2008) to approximate future wood supply impacts. These are subsequently used as inputs into a CGE model to estimate macro-economic impacts. Such methods can oversimplify

the response of forest conditions to climate change, and result in imprecise economic impact estimates.

An additional shortcoming of previous studies is they tend to only consider an aggregated wood supply input (i.e., stumpage value) when considering the economic impacts of climate change. However, hardwood and softwood have unique economic values, and are expected to be uniquely impacted by climate change (Brecka et al., 2020). As such, there is a need to differentiate between the hardwood forestry and logging (H-FOR) sector and the softwood forestry and logging (S-FOR) sector, and corresponding stumpage value inputs within CGE models to appropriately account for the economic impacts of climate change on different forestry sectors.

Recently, Lantz et al. (2022) attempted to address both the aforementioned shortcomings by: (i) refining their CGE model to distinguish between hardwood and softwood when examining the impacts of, and adaptation to, climate change in the forest sector; and (ii) coupling their CGE model with a forest management planning model (i.e., Woodstock[3]) parameterized to New Brunswick's Crownland Forest. Their forest modeling approach, however, is based on calibrated stand growth and yield modifiers that only reflect changes to forest succession on a relatively small land-base and do not consider the combined effects of climate change on forest productivity and

[3] Woodstock is a software developed and sold by Remsoft (www.remsoft.com/woodstock-optimization-studio/) that helps planning of forest management practices through a Monte Carlo simulation (Walters, 1993). Academic studies use Woodstock to examine how climate change and mitigation strategies will impact various components of a forest (Dhital et al., 2015; Dymond et al., 2020; Lundholm et al., 2019, 2020).

natural disturbances across the landscape, which may drive substantial changes in wood supply (e.g., Brecka et al. 2020).

Ecological studies have developed a robust modeling framework to help account for the complex ecological mechanisms that drive forest landscape dynamics in response to climate change. For instance, the PICUS-LANDIS II ecological modeling framework, here-after referred to as the PICUS-LANDIS framework, has been used to assess how the structure of forests will change under different climate change and forest management scenarios (Brecka et al., 2020; Boulanger et al., 2019, 2017; Taylor et al., 2017). The PICUS-LANDIS framework consists of two models. PICUS is a stand-level forest simulation model generally used to study forest stand dynamics (Lexer & Hönninger, 2001). PICUS has been used to estimate how different drivers (e.g., climate change and forest management) impact the germination, growth, and death of individual trees at the forest stand level (Irauschek et al., 2017; Seidl & Lexer, 2013). LANDIS-II is a spatially-explicit landscape-level forest simulation model that uses raster-based data to simulate both stand- and landscape scale forest dynamics across a region (Scheller et al., 2007). LANDIS-II has been extensively used to study how the effects of climate change (Scheller & Mladenoff, 2005), forest management (Scheller et al., 2011), and severity or frequency of natural disturbances (De Jager et al., 2019; Schrum et al., 2020; Sturtevant et al., 2009) impact the structure and composition of forest.

Brecka et al. (2020) used the PICUS-LANDIS framework along with the biomass harvested extension (v.3.0; Gustafson et al., 2000) to study how climate change will impact the biomass harvested of individual tree species across Canada, showing that as

forest structure changes due to climate change, so does the supply and composition of wood. Their results suggest the supply of economically important softwood species is expected to significantly decrease in eastern Canada, which is supported by Taylor et al., (2017), who also find some hardwood species may experience a significant increase in growth and abundance.

Although studies using the PICUS-LANDIS framework examine the impact climate change has on economically important species, they do not conduct a formal analysis of how this change will impact the economy. Joined with a CGE model, results stemming from these process-based forest models could provide an in-depth assessment of the macro-economic impacts of climate change on forests.

This study aims to enhance methods of estimating the ecological and economic impact of climate change on forests by joining the PICUS-LANDIS model with a CGE model to more reliably account for climate change effects on both forest stand and landscape-level dynamics. We apply this framework to the forest of New Brunswick, Canada, as a case study.

The remaining sections of this paper are formatted as follows. Section 2 provides an overview of the PICUS-LANDIS framework and the CGE model, as well as the coupling procedure and scenarios considered for the case-study region. Then, section 3 presents the results of both the ecological and economic analysis. Section 4 discusses the implications of the analysis as well as the limitations that occur under our analytical framework.

2.3 Methods and data

2.3.1 PICUS-LANDIS framework

The PICUS-LANDIS framework is comprised of two separate models simulating forest ecosystem processes at different spatial scales: PICUS and LANDIS-II. The coupling of these models is well-established and is used to study the impacts of climate change on different forest landscapes (e.g Boulanger et al., 2017, 2019; Boulanger & Pascual Puigdevall, 2021; Brecka et al., 2020; Taylor et al., 2017; Tremblay et al., 2018).

LANDIS-II is a spatially explicit raster-based forest landscape model that simulates both stand- and landscape level dynamics, including forest succession, seed dispersals and both anthropogenic (e.g., harvesting) and natural (e.g., fire, insect outbreaks) disturbances (Scheller et al., 2007). We set the resolution of cells to 250 m x 250 m, with each cell being assigned a specific 'land type'—a combination of unique soil and climate conditions assumed to be homogenous across the cell. When forest makes up less than 50% of the cell, it is assigned an inactive classification. Forest landscapes are initialized to conditions prevailing in the year 2000 using Canadian National Forest Inventory maps (Beaudoin et al., 2014) as well as provincial forest sample plot data[4].

To create the stand-level climate- and soil-sensitive dynamic inputs required to calibrate and operate LANDIS-II, we use outputs generated from the stand-level simulation model PICUS. PICUS (V1.5; Lexer & Hönninger, 2001) simulates the

[4] Additional details regarding model description as well as landscape initialization can be found in Boulanger et al. (2016) and Tremblay et al. (2018).

germination, growth and death of individual trees in interacting forest patches (100 m^2 in size). Patches are situated beside each other on a contiguous 10 m x 10 m grid to simulate a one-hectare forest stand area. PICUS accounts for the interactions between patches by using a 3D light sub-model along with simulating seed dispersal. This makes it possible to simulate how a change in climate and soil characteristics will impact individual trees within forest stands. We parameterize and calibrate PICUS to New Brunswick forest conditions using locally available forest inventory plot data as well as climate and soil data from McKenney et al. (2013) and Mansuy et al. (2014), respectively[5].

PICUS simulations are run for 300 years, starting on bare soil, for monospecific stands of each of seventeen tree species included in the analyses. Distinct simulations were run for each land type, using their soil characteristics under baseline climate conditions (conditions prevailing during the 1981-2010 climate normals period) as well as under climate conditions that should prevail on these land-types for three anthropogenic climate forcing scenarios known as Representative Concentration Pathways (RCP): RCP 2.6, RCP 4.5, and RCP 8.5 (van Vuuren et al., 2011). In order to depict changes in stand-level conditions throughout the 21st century, simulations are separately conducted using climate conditions prevailing during the 2011-40, 2041-70 and 2071-2100 time periods.

We use the species-, climate-, and land type-specific outputs from PICUS to produce dynamic stand-level inputs for the LANDIS-II Biomass Succession extension

[5] Additional details regarding model description and calibration can be found in Taylor et al. (2017).

(V4; Scheller & Mladenoff, 2004). This extension simulates how species- and age-specific cohorts of forests grow, age, and die according to species autecology and knowledge of forest succession. Dynamic parameters produced from PICUS include species establishment probabilities (*SEP*), maximum possible above-ground net primary productivity (*max*ANPP), and maximum above-ground biomass (*maxAGB*). A thorough description of how these inputs are produced, calibrated and validated can be found in Tremblay et al. (2018).

Anthropogenic disturbances are defined as harvesting activities in LANDIS-II and are accounted for using the Biomass Harvest extension (V4.0; Gustafson et al., 2000). We simulate harvesting prescriptions using forest management units (FMU) where specific user-defined rates may occur. In our simulations we simulate clear-cut harvesting which removes 100% of biomass of all cohorts selected to be harvested. In order for a cohort to be eligible to be harvested, it needs to be older than 60 years. Additionally, we assume that there is no preference for any particular species when harvesting. Individual clear-cut size is set to 12.5 ha, which is represented in LANDIS-II as two pixels (6.25 ha per pixel). This is based on the mean clear-cut patch size observed in the province with data obtained from New Brunswick's Forest stand inventory. We use data from the National Forestry Database (CCFM, 2020a) to determine the annual harvesting disturbance rate of 1%, which stays fixed across all scenarios.

Natural disturbances considered and simulated in this study include spruce budworm (SBW, *Choristoneura fumiferana* [Clem.]) outbreaks and forest fires. SBW

outbreaks are modeled using the Biological Disturbance Agent (BDA) extension (V5.0; Sturtevant et al., 2004) in LANDIS-II. BDA simulates the mortality of host trees during an SBW outbreaks, with the most susceptible host tree species being balsam fir, and white spruce and the least vulnerable being red and black spruce. Grid-cell level outbreaks occur as stochastic events with the likelihood of occurrences being influenced by the abundance of host trees in both the cell and neighboring (1-km radius) cells. We calibrate grid-cell level outbreaks using locally conducted studies (e.g., Hennigar et al. (2008)). Regional SBW outbreak disturbance regimes are calibrated using historical data, with outbreaks occurring on a 40 year cycle and affecting less than 5% of the total forest area in NB (Boulanger et al., 2012; MacLean, 1980).

To account for forest fires we use the LANDIS-II Base Fire extension. The extension simulates forest fires as a probabilistic event that is influenced by fire ignition and spread parameters derived for baseline and future time periods (Boulanger et al., 2014), and are further updated for individual climate change scenarios (Gauthier et al., 2015).

LANDIS-II simulations are conducted on a 10-year timestep, starting in the year 2000 and proceeding for 150 years (i.e., up to the year 2150). In simulations involving climate change, dynamic input parameters are set to change according to time period (i.e., 2011-20, 2041-50 and 2071-2080). We simulate five replicates for each scenario in order to take into account model stochasticity (mostly related to seed dispersal, dynamic inputs, as well as natural and anthropogenic disturbances). For a given simulation, we determine the biomass of wood harvested by species per time step. The

biomass of wood is aggregated by type of wood (hardwood or softwood), and a growth rate is calculated between periods. These growth rates are applied to the hardwood and softwood stumpage endowment within the CGE model, as explained below.

2.3.2 Computable General Equilibrium (CGE) model

We use a single-region, recursively-dynamic CGE model to analyze the economic impact of climate change altering New Brunswick's forest structure and composition. The model builds on Ochuodho et al., (2012) and Liu et al., (2019) with two additional modifications. First, we disaggregate the forestry and logging sector into the H-FOR and S-FOR sectors. In doing so, we also add both hardwood and softwood as factors or production in their respective sectors. Lastly, we use Statistics Canada's Detail level Symmetric Input Output Table (Statistics Canada, 2020b) to incorporate 27 sectors (Table 2.1) into the CGE model with six being defined as wood-related manufacturing sectors (Table 2.2). These six wood-related manufacturing sectors are heavily dependent on both the S-FOR and H-FOR sectors for intermediate inputs (Table 2.3). As such, these sectors are sensitive to both a change in quantity and composition of New Brunswick's wood supply. Including these sectors in the study provides a better understanding of how a change in New Brunswick's forests will impact the economy.

Table 2.1 Production sectors included in New Brunswick's CGE model

sec1	Crop and animal production (CROP)	sec15	Other Manufacturing (OTH-MANUF)
sec2	Softwood forestry and logging (S-FOR)	sec16	Wholesale trade (TRADES)
sec3	Hardwood forestry and logging (H-FOR)	sec17	Retail trade (RET)
sec4	Fishing hunting & trapping (FISH)	sec18	Transportation (TRANSP)
sec5	Support activities for agricultures & forestry (SUPP)	Sec19	Information (INFO)
sec6	Mining quarrying, oil, & gas extraction (OILGAS)	Sec20	Finance (FIN)
sec7	Utilities (UTL)	sec21	Professional (PROF)
sec8	Construction (CONST)	sec22	Administration (ADMIN)
sec9	Sawmills & wood preservation (SAW-MANUF)	sec23	Education (EDUC)
sec10	Veneer plywood manufacturing (VEN-MANUF)	sec24	Health care (HEALTH)
sec11	Other wood product manufacturing (OW-MANUF)	sec25	Entertainment (ENT)
sec12	Pulp paper & carboard mills (PUP-MANUF)	sec26	Accommodation & food services (ACC)
sec13	Converted paper product manufacturing (CP-MANUF)	sec27	Other goods & services (OG&S)
sec14	Printing and related activities (PR-MANUF)		

Table 2.2 Wood-related manufacturing sectors in New Brunswick's CGE model

sec9	Sawmills & wood preservation (SAW-MANUF)	sec12	Pulp paper & carboard mills (PUP-MANUF)
sec10	Veneer plywood manufacturing (VEN-MANUF)	sec13	Converted paper product manufacturing (CP-MANUF)
sec11	Other wood product manufacturing (OW-MANUF)	sec14	Printing & related activities (PR-MANUF)

Table 2.3 Demand for softwood and hardwood intermediate goods by sectors in New Brunswick in 2015 (2015 dollars)

	SAW-MANUF	VEN-MANUF	OW-MANUF	PUP-MANUF	CP-MANUF	PR-MANUF	Rest of the economy
S-FOR	353.48	8.94	6.27	39.32	1.94	0.07	55.13
H-FOR	30.52	0.72	0.50	133.33	0.78	0.03	22.25

The CGE model treats New Brunswick as a small open economy. This means that sectors have access to the international market through imports and exports. As a small economy, firms do not influence the world price, supply, or demand of commodities. Additionally, at the end of each period, all markets within the economy are cleared.

The model incorporates four factors of production: capital, labour, hardwood, and softwood. Each factor is assumed to be owned by the household and purchased by sectors through the payment of rent, wages, and stumpage. Capital and labour are mobile across all sectors, while hardwood and softwood are exclusively demanded by their corresponding forestry and logging sector.

We use a bundling technique (Timilsina et al., 2012)[6] within a multifactor production function (Lofgren et al., 2002) to define the production technology. This leads to the production block containing three separate production nests. The first nest is a Leontief production function that determines a firm's optimal combination of intermediate goods and wood-capital-labour bundle[7]. The second nest is a three-factor constant elasticity of substitution (CES) production function that allows firms to select the amount of hardwood, softwood and capital-labour bundle that they require. The third nest is a two-factor CES production function that allows firms to select their optimal amount of capital and labour. Firms' outputs are constricted by the zero-profit condition as well as the supply of intermediate goods and the availability of factors of production.

[6] The bundling approach allows us to restrict the substitutability of hardwood and softwood stumpage for the capital-labour bundle, while still allowing capital and labour to be substitutable with each other.
[7] The Leontief production function implies that inputs are used in a fixed portion to each other.

The household sector receives income by providing labour, capital, hardwood, and softwood to the market as well as general transfers from the government. The household maximizes its utility based on a Cobb-Douglas production function. Their utility function is restricted by a budget constraint which is based on the household's after tax and savings income.

Each firm within the CGE model is assumed to produce a unique commodity, with commodities being sold to either the domestic market or exported to the international market. The domestic market is made up of intermediate goods, investments, and consumption by the households and government. Firms have access to the international market through an Armington and Constant Elasticity of Transformation (CET) function. The Armington function[8] is used to determine the amount of commodities the firms import into the economy, while the CET function allows firms to choose if they sell their output to either the local economy or the international market. In this model imports, exports and tariffs are all paid using local currency and converted to the world price using an exchange rate.

The government represents all public sectors and collects revenue from taxes (tax on income, tax on factors of production, and tax on consumption) and tariffs. The government also uses capital, labour and commodities with their demand being determined with a Cobb Douglas function. Additionally, the government pays out two

[8] The Armington function described by Armington (1969) allow firms to have a preference between imported and domestically produced goods. The Armington function allows the demand of imported goods to be a function of the supply of domestic goods, as well as domestic and international prices.

different transfers to the household. The first transfer is a general transfer and is treated as a constant within the model. The second transfer is an unemployment benefit, and as such is directly related to unemployment within the economy. The model incorporates unemployment using a Philips curve[9], with the initial rate being calibrated to New Brunswick using Statistics Canada's Labour Force Characteristics data set (Statistics Canada, 2015).

Investments and savings are incorporated within the CGE model. Household's saving is determined by their marginal propensity to save and is calibrated to the initial year of the model (i.e., 2015) and held constant throughout the simulation. However, household savings can change as they dependent on the household's income. A representative bank purchases commodities from sectors, which is represented within the model as investments. Investments are determined by total savings, which are the aggregated sum of household savings, foreign savings and government savings.

Within the CGE model, there are several market closures, including those for foreign savings, government savings, general transfers, and the endowment of capital, labour, hardwood wood and softwood wood. Additionally, the price of labour is set to one in order to act as the numeraire.

The model is coded and solved in General Algebraic Modeling System (GAMS) version 31.1.1 (GAMS Development Corporation, 2020) using the conopt3 solver. Using

[9] The Philips curve was first hypothesised by Phillips (1958) and later defined by Friedman (1968) and Phelps (1967, 1968). The equation describes an inverse relationship between real wages and the voluntary unemployment rate within an economy. In the context of the CGE model, if real wages increase, voluntary unemployment decreases.

the loop command, the model is turned into a recursive dynamic model with growth rates being applied to the capital, labour, hardwood, and softwood endowments, as defined under each scenario.

The growth rate for labour Is based on projections from New Brunswick's Government (Government of New Brunswick, 2018). Specifically, New Brunswick is projected to experience minor to no growth in population as well as a slight decrease (-0.3% annually) in labour force over the foreseeable future. As such, we set labour growth within the CGE model at 0%.

The growth rate for capital is determined using an equation that incorporates the price of capital, total savings, and a steady state growth rate. The steady state growth rate (0.22%) is calibrated to ensure that the CGE model aligns with the projected annual change of unemployment (-0.2%) within the province (Government of New Brunswick, 2018). The growth rates for hardwood and softwood supply are explained in section 2.4 below.

The CGE model is calibrated to the New Brunswick economy by constructing a Social Accounting Matrix (SAM). The SAM is constructed using New Brunswick's 2015 Symmetric input-output table (Statistics Canada, 2020), household accounts (Statistics Canada, 2020c), and hardwood and softwood stumpage revenues (CCFM, 2020b). The symmetric input-out table contains 230 sectors which we aggerate to 27 sectors (Table 2.1). The input-out table is used to determine the demand for intermediate goods, imports, exports, investments, labour, capital and consumption by the government and

households. The Household account is used to determine transfers between the government and the household.

The original input-out table does not include stumpage revenues. To obtain these for use in our SAM, we first split stumpage out of the forestry and logging sector's capital (under "other operating surplus"). Using an estimate of total royalties from Crownland in 2015 (CCFM, 2020b) in conjunction with both the quantity of wood harvested by grade and species (CCFM, 2020a) and local stumpage rates (New Brunswick's Federation of Woodlot Owners, 2015)[10], we determined the proportion of Crownland royalties generated by grade and species. These values are scaled-up to the entire province by adding the equivalent proportion of Private Forest land stumpage, obtained using similar methods as above. Adding together the total Crownland royalties and Private land stumpage by grade and species allows us to estimate the total stumpage value that is paid by the H-FOR vs S-FOR sectors in 2015.

To disaggregate the forestry and logging sector into H-FOR and S-FOR sectors in the SAM, we use the quantity of wood harvested by grade and species, local stumpage prices by grade and species and New Brunswick's 2015 supply and use table (Statistics Canada, 2021). The supply and use table allows us to determine the wood-related manufacturing sector's (Table 2.3) specific demand in dollar value for wood products by grade. Using the proportional breakdown of the value of wood by grade per species

[10] We assume here that the prices of Crownland stumpage are identical to those on private land. This assumption is justified on grounds that the New Brunswick government has a policy in place to price Crown stumpage at private market rates (NBFPC, 2016).

in conjunction with the supply and use table we determined each sector's demand for wood products by grade and species.

Disaggregating the forestry and logging sector into hardwood vs softwood sub-sectors creates an imbalance in the SAM. To rebalance the SAM, we create a linear solver[11] that redistributes the imbalance to all interactions that occurred between the forestry and logging sectors and other entities that are not included within the supply and use table. This process allows us to determine the demand for H-FOR vs S-FOR sector output for sectors that are not included in the supply and use table.

To complete the calibration of the CGE model, we require several elasticity parameters that represent an agent's willingness or ability to change their demand between goods and/or factors of production when market conditions change. We collect the following elasticities from the peer-reviewed literature: (i) the elasticity of substitution between factors of production (Okagawa & Ban, 2008); (ii) the elasticity of household consumption (Huff et al., 2012); (iii) the Armington elasticities between imports and domestically produced goods (Huff et al., 2012); and (iv) the CET elasticities between exports and value-added goods and services (Arndt et al., 2001). Following the methodology of past studies, we set the elasticities of substitution between hardwood/softwood stumpage and other factors of production in the forestry and logging sectors to a value close to zero (Withey et al., 2016)[12].

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[11] The linear solver is created in Microsoft Excel and is based on the RAS approach (McDougall, 1999). Cells that are disaggregated using the supply and use table (Statistics Canada, 2018b) are treated as constants while the remaining cells are multiplied by a fixed proportion.

[12] There is no published data regarding the elasticity of substitution between stumpage and the capital-labour bundle. Hence, we follow past CGE studies that have assumed that the rate of substitution is low as stumpage is a required factor of production for the forestry & logging sectors.

2.3.3 Joining the models

To join the PICUS-LANDIS framework with the CGE model, we use the Biomass Harvest extension in the former model to determine above-ground biomass harvested per species. This allows us to determine the growth rate of hardwood and softwood supply under different climate change scenarios. This growth is then applied to the CGE model using a dynamic growth function for the endowment of hardwood and softwood, assuming the percentage change in biomass harvested results in an equivalent percentage change in wood supply. This coupling process allows the PICUS-LANDIS framework to determine the change in supply of hardwood and softwood between periods, while the CGE model is responsible for calculating the economic impact that occurs due to the change in hardwood and softwood stumpage.

2.3.4 Scenarios and climate data

We considered four future climate scenarios in our analysis – baseline (i.e., no climate change), RCP 2.6, RCP 4.5, and RCP 8.5 (van Vuuren et al., 2011). For each scenario, monthly climate data is interpolated across the study area from climate station records using estimates from McKenney et al. (2013). Baseline climate corresponds to the observed climate between 1981-2010. Future climate projections for RCP 2.6, 4.5 and 8.5 scenarios are collected from the Canadian Earth System Model v.2 (CanESM2) with values representing peak radiative forcing of 2.6 $W \cdot m^{-2}$, 4.5 $W \cdot m^{-2}$ and 8.5 $W.m^{-2}$ by 2100, respectively. Depending on the severity of climate change, mean annual temperature may increase between 1.5°C and 6°C, with the largest

increase occurring under RCP 8.5 (Lennmen et al., 2018), while annual mean precipitation could increase upwards of 18% by 2080 (Lines et al., 2008).

For each of the climate change scenarios considered, we use the PICUS-LANDIS framework to assess individual tree species above-ground biomass (t/ha) trends over the 2015-2150 period. We also use the CGE model to present sector-level output and prices, along with a series of macro-economic variables including the values of: gross domestic product (GDP); household income (Y); equivalent variation (EV)[13]; household consumption); government consumption (CG); investment (INV); exports (EXP); imports (IMP); domestic output (XD); domestic output delivered domestically (XDD); labour (L); and capital (K) over the same period. Cumulative present values are calculated using a 2% real discount rate reflecting the rate of return of long-term government bonds in Canada as of 2015 (Statistics Canada, 2022).

2.4 Results

2.4.1 Ecological impacts

The results of the PICUS-LANDIS framework simulations show that climate change will have a substantial impact on New Brunswick's forests. Above-ground biomass decreases under all three climate change scenarios relative to the baseline scenario, with the largest decrease occurring under the most severe climate forcing

[13] Equivalent variation is a measure of social welfare. It represents a change in income, at current prices, that would have the same effect on consumer utility as would a change in prices, with income unchanged. It is measured as the difference between: (i) the supernumerary income that would exist under the proposed change divided by a price index that reflects the change in prices under the proposed change; and (ii) the supernumerary income that exists under baseline conditions.

scenario (RCP 8.5, Figure 2.1). The reduction in biomass occurs slowly at first, however, after 2080 there is an increase in the rate at which biomass decreases.

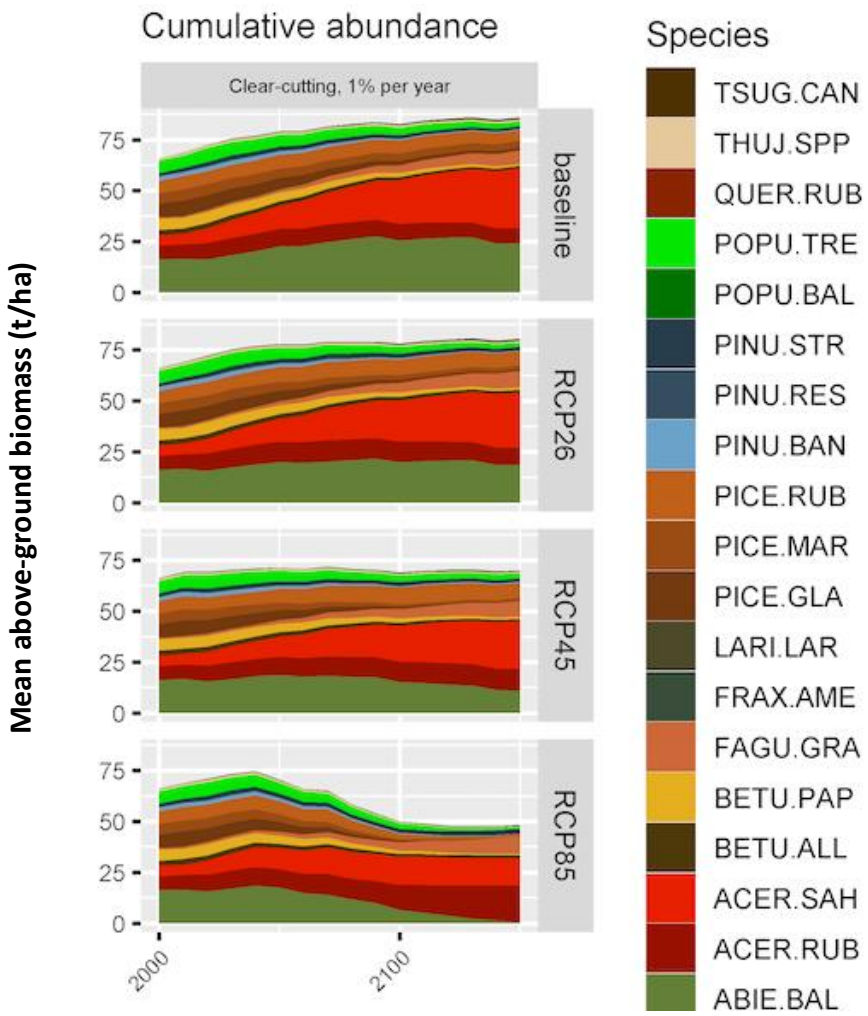

Figure 2.1 Abundance of individual species in New Brunswick (mean above ground biomass, t/ha)

As the composition of New Brunswick's forests changes under the climate change scenarios, so does the biomass harvested of individual cold-adapted species (Table 2.4). White spruce, balsam fir, red spruce and sugar maple all experience a large reduction in biomass harvested of 88%, 81%, 65%, and 36%, respectively, under RCP 8.5 by 2150 relative to the baseline climate scenario. There is also a noticeable reduction in biomass harvested under RCP 2.6 and RCP 4.5 for white spruce (64%, 33%) and balsam fir (22%, 40%).

Table 2.4 Biomass harvested of individual species by scenario in New Brunswick in 2080 and 2150 (% differences from the Baseline scenario)

		Scenarios					
		RCP 2.6 (% diff)		RCP 4.5 (% diff)		RCP 8.5 (% diff)	
		2080	2150	2080	2150	2080	2150
Softwood species	Balsam fir	-8.37%	-22.29%	-14.35%	-39.93%	-15.02%	-80.73%
	Easter larch	0.17%	-6.22%	-0.31%	-43.13%	-1.05%	-76.13%
	White spruce	-6.37%	-33.18%	-12.46%	-64.46%	-11.95%	-88.69%
	Black spruce	-2.88%	-42.16%	-12.66%	-70.84%	-10.88%	-90.77%
	Red spruce	-0.33%	23.93%	0.67%	59.73%	-11.13%	-65.13%
	Jack pine	5.46%	-29.17%	5.60%	-12.10%	0.83%	-7.68%
	Red pine	-2.92%	34.67%	-2.16%	33.17%	3.40%	15.80%
	White pine	9.39%	26.95%	-5.75%	16.46%	0.50%	52.51%
	Cedar	0.72%	-0.02%	-5.87%	-15.79%	-8.89%	-48.93%
	Eastern hemlock	5.90%	0.56%	-6.39%	-22.01%	-4.39%	-38.42%
Hardwood species	Red maple	8.38%	25.15%	-1.46%	30.74%	3.96%	95.45%
	Sugar maple	-4.19%	-6.31%	-11.60%	-17.19%	-8.54%	-36.25%
	Yellow birch	6.10%	24.65%	-0.28%	10.72%	0.68%	7.59%
	White birch	0.34%	8.19%	-1.85%	-1.87%	-0.78%	-21.14%
	American beech	12.45%	22.78%	13.82%	27.70%	7.20%	50.95%
	Poplar	-1.29%	-13.14%	-4.17%	-10.82%	-3.04%	-2.20%

While many softwood species experience a reduction in biomass harvested, two softwood species that experience substantial increases are red pine (RCP 2.6: 35%, RCP 4.5: 33% and RCP 8.5: 16%) and white pine (RCP 2.6: 27%, RCP 4.5: 16% and RCP 8.5: 52%) by 2150 when compared to the baseline scenario. Red spruce also had a significant increase (24%) in biomass harvested under RCP 2.6 by 2150; however, it experiences a decrease in biomass harvested under RCP 4.5 and RCP 8.5 by 2150.

Several hardwood species experience increases in biomass harvested across all scenarios, including red maple (RCP 2.6: 25%, RCP 4.5: 31% and RCP 8.5: 95%), American beach (RCP 2.6: 23%, RCP 4.5: 28% and RCP 8.5: 51%) and yellow birch (RCP 2.6: 25%, RCP 4.5: 11% and RCP 8.5: 8%). However, sugar maple and poplar experience a reduction in biomass harvested across all climate change scenarios, with sugar maple experiencing its largest reduction under RCP 8.5 (36%), followed by RCP 4.5 (17%) and RCP 2.6 (6%). Poplar experiences the largest reduction under RCP 2.6 (13%), which is followed by RCP 4.5 (11%) and lastly RCP 8.5 (2%).

The decrease in biomass harvested for most softwood species relative to baseline climate translates to a reduction in total softwood supply under all climate change scenarios, with the most severe decrease of 73% taking place under RCP 8.5 by 2150 (Figure 2.2). Simulations under RCP 2.6 and RCP 4.5 see more moderate reductions in softwood supply of 16% and 28%, respectively, when compared to those simulated under the baseline climate by 2150.

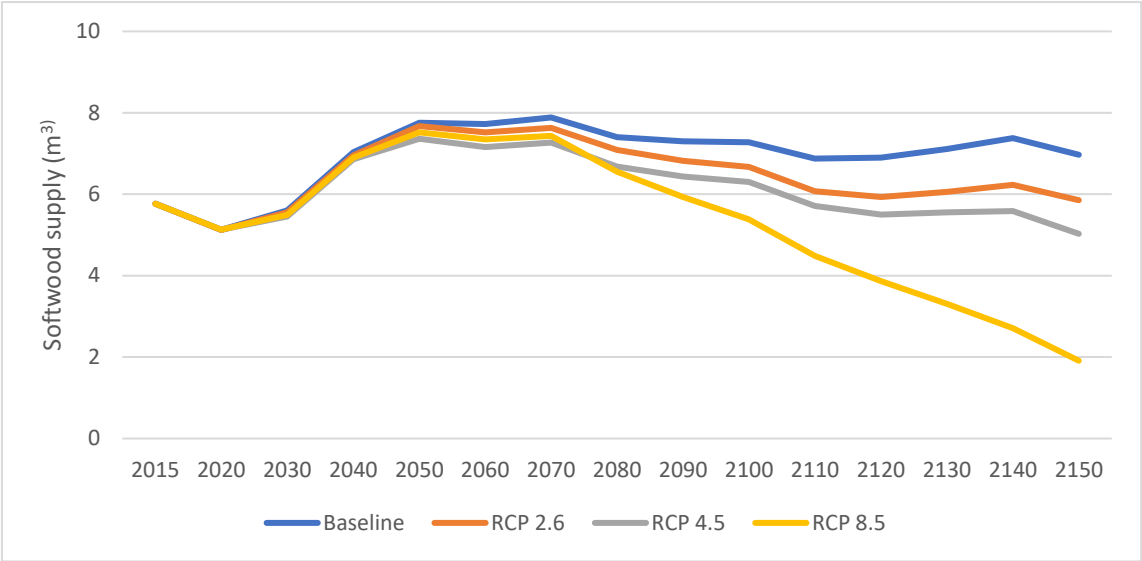

Figure 2.2 Aggregated supply of softwood in New Brunswick from 2015-2150 (m^3 mill)

The increase in biomass harvested of warm adapted hardwood species relative to the baseline climate scenario translates to an increase in total hardwood supply by 4% and 1% under RCP 2.6 and RCP 8.5, respectively, by 2150 (Figure 2.3). The increase in hardwood supply under RCP 2.6 is due to the increase in the majority of hardwood species (Table 2.4), as four of the six experience an increase in biomass harvested when compared to the baseline climate scenario. Meanwhile, under RCP 8.5, the 1% increase in hardwood supply is due to the increase in biomass harvested of both red maple and American beech, which counters the reduction in biomass of sugar maple and white birch. The only scenario that sees a decrease in hardwood supply relative to the baseline is RCP 4.5 where it exhibits a decrease of 2% by 2150. This decrease is a result of reductions in sugar maple and poplar, with an increase in biomass harvested of red maple and yellow birch.

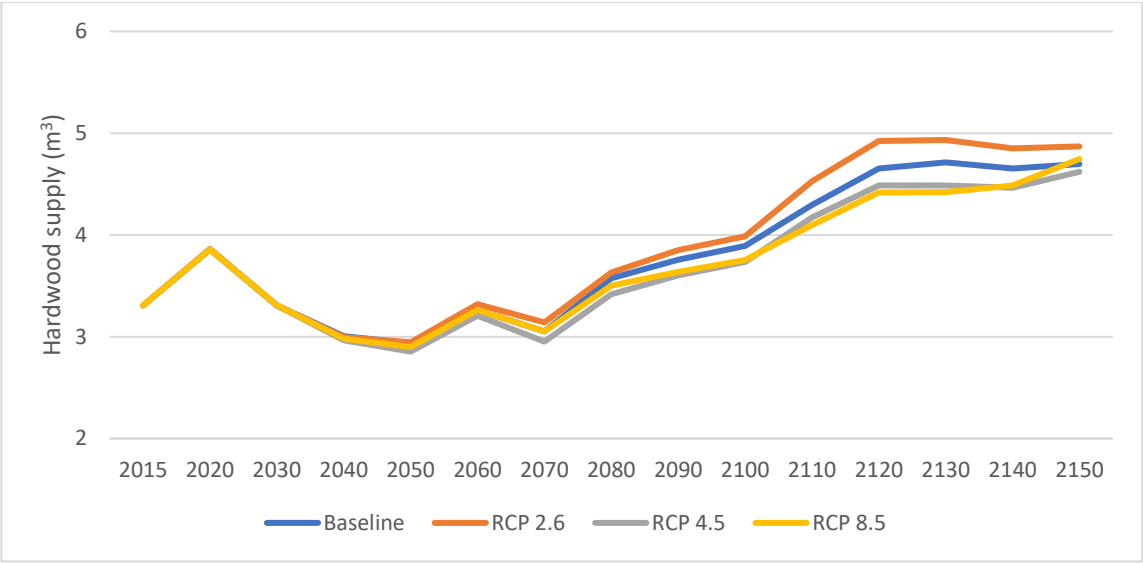

Figure 2.3 Aggregated supply of hardwood in New Brunswick from 2015-2150 (m^3 mill)

The simulated changes in hardwood and softwood harvested biomass have a direct impact on the composition of wood supply within New Brunswick. For instance, in 2015, softwood accounts for 53% of wood used within New Brunswick. By 2150, this proportion becomes much smaller under each climate change scenario (Baseline: 48.88%; RCP 2.6: 43.65%; RCP 4.5: 41.24%; and RCP 8.5: 20.61%). The change in wood composition, especially under RCP 8.5, is largely driven by the reduction in abundance of softwood species in New Brunswick's forests.

2.4.2 Economic impacts

2.4.2.1 Sector-specific impacts

The change in hardwood and softwood supplies tend to have inverse impacts on their associated stumpage prices under all scenarios (Figures 2.4 and 2.5), following neo-classical economic theory. Specifically, softwood stumpage prices tend to decrease and remain similar under all scenarios up to 2080. After this date, the softwood stumpage price increases substantially under RCP 8.5 (by up to seven-fold) compared to the baseline. Increases are also observed under RCP 2.6 and RCP 4.5 (by up to two-fold) compared to the baseline. Hardwood stumpage prices on the other hand tend to increase and remain at similar levels under all scenarios up to 2070. After this date, prices continuously decrease until the end of the temporal scope of this study across all scenarios.

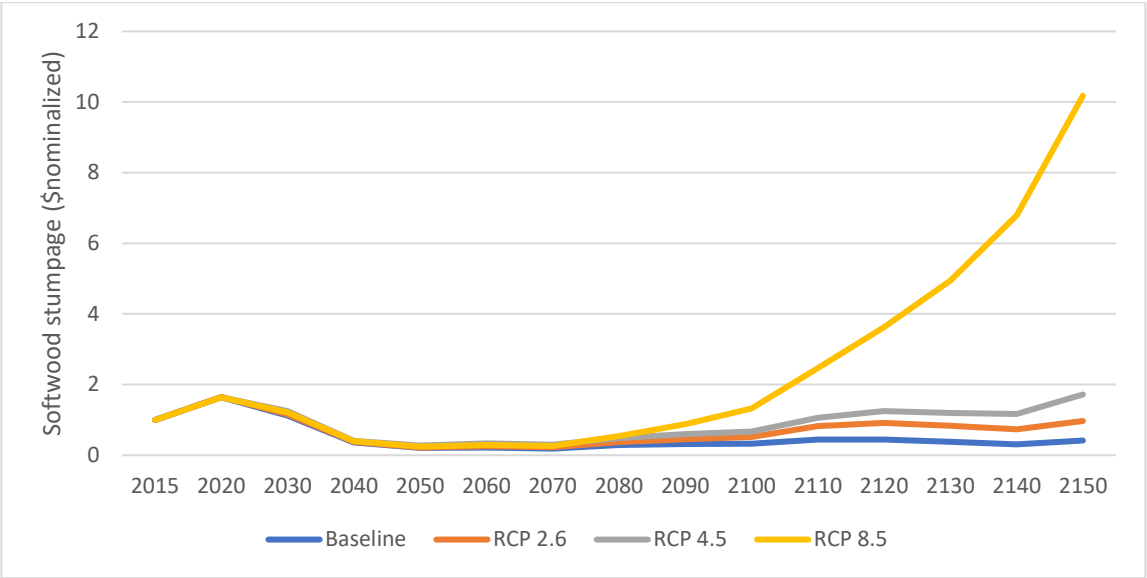

Figure 2.4 Softwood stumpage price in New Brunswick between 2015-2150 ($nominalized, relative to 2015)

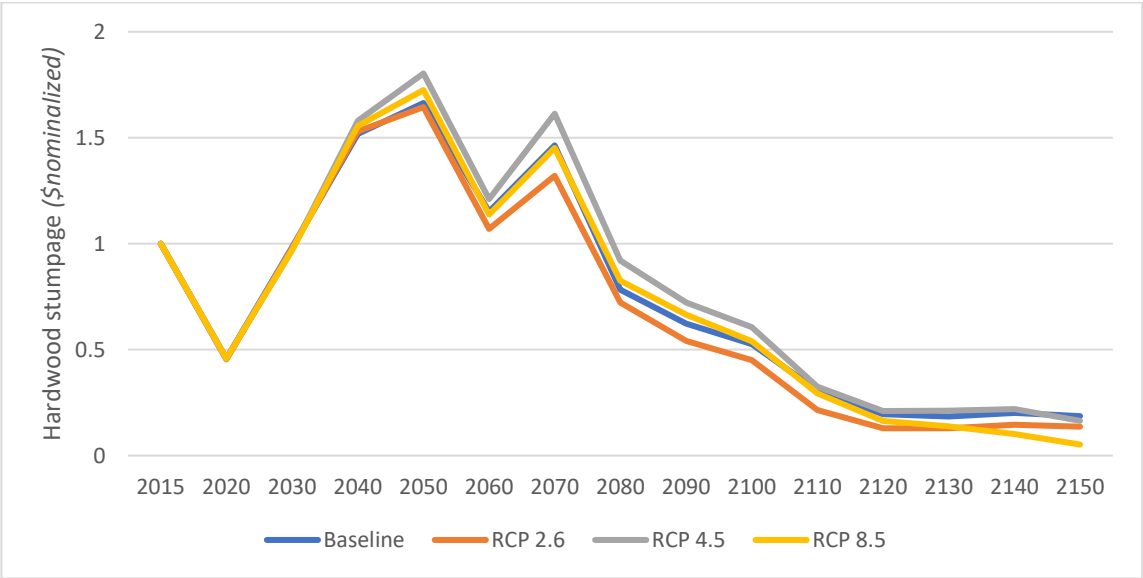

Figure 2.5 Hardwood stumpage prices in New Brunswick between 2015-2150 ($nominalized, relative to 2015)

Output prices for S-FOR and H-FOR sectors tend to follow similar changes as their respective stumpage prices over time (Table 2.6). Specifically, the S-FOR sector experiences an increase in its output price across all scenarios with the largest increase in price occurring under RCP 8.5. This increase is driven by both the reduction in output as well as the increase in softwood stumpage prices (Figure 2.4). The price of output in the H-FOR sector, on the other hand, increases under RCP 4.5 and decreases under RCP 2.6 and RCP 8.5 when compared to the baseline (Table 2.5), similar again to the changes in hardwood stumpage prices (Figure 2.5).

Table 2.5 Sectoral output prices in New Brunswick by scenario in 2080 and 2150 (% difference from Baseline)

	Scenarios					
	RCP 2.6 (% diff)		RCP 4.5 (% diff)		RCP 8.5 (% diff)	
Sector	2080	2150	2080	2150	2080	2150
CROP	0.01%	0.05%	0.03%	0.12%	0.03%	0.57%
S-FOR	0.19%	1.19%	0.49%	2.67%	0.61%	16.14%
H-FOR	-0.18%	-0.16%	0.44%	0.01%	0.15%	-0.12%
FISH	0.00%	0.03%	0.02%	0.06%	0.02%	0.30%
SUPP	0.00%	0.03%	0.02%	0.07%	0.02%	0.33%
OILGAS	0.00%	0.04%	0.03%	0.10%	0.03%	0.50%
UTL	0.01%	0.05%	0.03%	0.12%	0.03%	0.56%
CONST	0.01%	0.06%	0.04%	0.14%	0.04%	0.67%
SAW-MANUF	0.08%	0.52%	0.24%	1.16%	0.28%	5.86%
VEN-MANUF	0.05%	0.33%	0.15%	0.73%	0.18%	3.48%
OW-MANUF	0.05%	0.30%	0.13%	0.67%	0.16%	3.20%
PUP-MANUF	0.01%	0.21%	0.16%	0.51%	0.14%	2.51%
CP-MANUF	0.01%	0.25%	0.20%	0.62%	0.17%	3.09%
PR-MANUF	0.01%	0.09%	0.06%	0.21%	0.06%	1.02%
OTH-MANUF	0.01%	0.08%	0.05%	0.19%	0.05%	0.86%
TRADES	0.00%	0.03%	0.02%	0.07%	0.02%	0.35%
RET	0.00%	0.03%	0.02%	0.06%	0.02%	0.30%
TRANSP	0.00%	0.03%	0.02%	0.07%	0.02%	0.35%
INFO	0.00%	0.04%	0.03%	0.10%	0.03%	0.46%
FIN	0.00%	0.03%	0.02%	0.06%	0.02%	0.28%
PROF	0.00%	0.02%	0.01%	0.05%	0.01%	0.25%
ADMIN	0.00%	0.02%	0.02%	0.06%	0.02%	0.28%
EDUC	0.00%	0.02%	0.01%	0.05%	0.01%	0.24%
HEALTH	0.00%	0.03%	0.02%	0.07%	0.02%	0.32%
ENT	0.00%	0.03%	0.02%	0.07%	0.02%	0.31%
ACC	0.00%	0.04%	0.02%	0.09%	0.02%	0.41%
OG&S	0.00%	0.03%	0.02%	0.06%	0.02%	0.29%

Wood-related manufacturing sectors also tend to experience price increases under each climate change scenario relative to the baseline (Table 2.5). The largest price increases in these sectors tend to occur under RCP 8.5, where S-FOR and H-FOR sector output reductions are the largest. Interestingly, the decrease in the value of H-FOR output does not have a substantial impact on the price of wood-related goods. Sectors that are not associated with the forestry and logging sectors or wood-related activities see a minor increase in the price of their output across all climate change scenarios compared to the baseline.

The sector-specific price is multiplied by the sector-specific physical output quantity value (Table 2.6) to determine the sector-specific output value. The Sector-specific output values tend to remain similar under all scenarios up to 2080, with climate change scenarios tending to cause slightly lower levels compared to those under the baseline (Table 2.7). For instance, the S-FOR sector experiences a decrease in output under all climate change scenarios relative to the baseline (RCP 2.6: -1%; RCP 4.5: -2%; and RCP 8.5: -3%). This causes a relatively small trickle-down effect as wood-related manufacturing sectors also experience slight decreases in value of output. Veneer manufacturing is the most impacted wood-related sector with the value of their output decreasing by 4% under RCP 8.5 when compared to the baseline. The H-FOR sector experiences a 0.40% increase in output in the year 2080 under RCP 2.6. However, under the remaining climate change scenarios, the H-FOR sector experiences a decrease in output of 2% and 1% under RCP 4.5 and RCP 8.5, respectively.

Table 2.6 Sectoral physical output in New Brunswick by scenario in 2080 and 2150 (2015 dollars, % difference from Baseline)

	Scenarios							
	Baseline ($ millions)		RCP 2.6 (% diff)		RCP 4.5 (% diff)		RCP 8.5 (% diff)	
Sectors	2080	2150	2080	2150	2080	2150	2080	2150
CROP	846.8	884.2	0.06%	0.68%	0.44%	1.61%	0.43%	7.45%
S-FOR	500.4	506.7	-0.73%	-5.15%	-2.35%	-11.58%	-2.72%	-57.91%
H-FOR	197.5	214.5	0.40%	-1.10%	-2.21%	-3.60%	-1.35%	-16.82%
FISH	362.5	375.7	0.09%	1.01%	0.66%	2.39%	0.64%	11.23%
SUPP	91.1	94.5	-0.23%	-2.47%	-1.55%	-5.83%	-1.52%	-28.27%
OILGAS	720.2	761.4	0.09%	0.97%	0.63%	2.29%	0.61%	10.70%
UTL	1572.5	1639.0	-0.01%	-0.19%	-0.15%	-0.46%	-0.13%	-2.11%
CONST	4294.1	4450.3	-0.01%	-0.13%	-0.08%	-0.30%	-0.08%	-1.43%
SAW-MANUF	909.7	929.6	-0.39%	-3.04%	-1.61%	-6.86%	-1.74%	-30.39%
VEN-MANUF	219.8	217.6	-1.39%	-7.33%	-2.72%	-15.12%	-3.72%	-53.60%
OW-MANUF	179.9	173.9	-0.46%	-2.54%	-0.94%	-5.41%	-1.27%	-23.58%
PUP-MANUF	1447.4	1521.4	0.02%	-1.55%	-1.48%	-4.04%	-1.18%	-19.10%
CP-MANUF	503.2	528.5	0.02%	-1.73%	-1.66%	-4.53%	-1.33%	-21.38%
PR-MANUF	24.2	24.7	0.02%	0.03%	-0.03%	0.02%	0.00%	-0.20%
OTH-MANUF	14803.2	15595.9	0.08%	0.89%	0.58%	2.09%	0.56%	9.71%
TRADES	1697.7	1757.1	0.01%	0.10%	0.07%	0.24%	0.06%	1.08%
RET	3143.8	3246.5	-0.01%	-0.07%	-0.04%	-0.16%	-0.04%	-0.76%
TRANSP	3929.9	4093.8	-0.03%	-0.38%	-0.27%	-0.91%	-0.25%	-4.08%
INFO	1432.3	1489.2	0.00%	-0.03%	-0.02%	-0.08%	-0.02%	-0.43%
FIN	8359.6	8634.2	-0.01%	-0.08%	-0.05%	-0.18%	-0.05%	-0.86%
PROF	1536.3	1594.4	-0.01%	-0.06%	-0.04%	-0.14%	-0.04%	-0.66%
ADMIN	2132.7	2230.0	-0.02%	-0.25%	-0.17%	-0.59%	-0.16%	-2.70%
EDUC	140.6	145.9	-0.01%	-0.11%	-0.07%	-0.26%	-0.07%	-1.23%
HEALTH	1419.3	1478.0	-0.01%	-0.07%	-0.05%	-0.17%	-0.05%	-0.81%
ENT	377.6	391.1	-0.01%	-0.14%	-0.09%	-0.33%	-0.09%	-1.54%
ACC	1472.5	1544.1	-0.01%	-0.09%	-0.06%	-0.22%	-0.06%	-1.05%
OG&S	1335.2	1394.1	-0.01%	-0.10%	-0.07%	-0.24%	-0.06%	-1.15%

Table 2.7 Sectoral output value in New Brunswick by scenario in 2080 and 2150 (% difference from Baseline)

	Scenarios							
	Baseline ($ millions)		RCP 2.6 (% diff)		RCP 4.5 (% diff)		RCP 8.5 (% diff)	
Sectors	2080	2150	2080	2150	2080	2150	2080	2150
CROP	833.4	857.0	0.07%	0.73%	0.48%	1.73%	0.46%	8.06%
S-FOR	486.1	486.8	-0.54%	-4.02%	-1.87%	-9.21%	-2.13%	-51.12%
H-FOR	193.5	203.1	0.22%	-1.26%	-1.78%	-3.59%	-1.20%	-16.92%
FISH	358.9	368.3	0.10%	1.04%	0.68%	2.46%	0.66%	11.56%
SUPP	89.8	91.9	-0.23%	-2.44%	-1.54%	-5.77%	-1.50%	-28.03%
OILGAS	706.9	734.0	0.09%	1.01%	0.66%	2.39%	0.64%	11.25%
UTL	1539.7	1571.8	-0.01%	-0.14%	-0.11%	-0.34%	-0.10%	-1.55%
CONST	4235.0	4332.2	-0.01%	-0.06%	-0.04%	-0.16%	-0.04%	-0.77%
SAW-MANUF	891.2	899.0	-0.31%	-2.53%	-1.38%	-5.78%	-1.47%	-26.31%
VEN-MANUF	215.5	210.2	-1.34%	-7.03%	-2.58%	-14.50%	-3.55%	-51.98%
OW-MANUF	177.3	169.7	-0.42%	-2.24%	-0.80%	-4.78%	-1.11%	-21.13%
PUP-MANUF	1420.7	1468.1	0.03%	-1.34%	-1.32%	-3.55%	-1.04%	-17.07%
CP-MANUF	494.0	510.2	0.03%	-1.49%	-1.46%	-3.94%	-1.16%	-18.95%
PR-MANUF	23.8	24.1	0.02%	0.11%	0.04%	0.23%	0.06%	0.82%
OTH-MANUF	14546.1	15071.5	0.09%	0.97%	0.63%	2.28%	0.61%	10.66%
TRADES	1672.0	1705.1	0.01%	0.13%	0.09%	0.32%	0.08%	1.43%
RET	3101.5	3160.9	0.00%	-0.04%	-0.03%	-0.10%	-0.03%	-0.46%
TRANSP	3867.5	3965.9	-0.02%	-0.35%	-0.25%	-0.83%	-0.23%	-3.75%
INFO	1404.9	1433.4	0.00%	0.01%	0.00%	0.01%	0.00%	0.03%
FIN	8251.1	8414.5	0.00%	-0.05%	-0.03%	-0.12%	-0.03%	-0.58%
PROF	1520.4	1561.6	0.00%	-0.04%	-0.02%	-0.09%	-0.02%	-0.41%
ADMIN	2105.5	2174.2	-0.02%	-0.23%	-0.15%	-0.54%	-0.15%	-2.43%
EDUC	139.2	142.9	-0.01%	-0.09%	-0.06%	-0.21%	-0.06%	-0.99%
HEALTH	1399.3	1437.1	0.00%	-0.04%	-0.03%	-0.10%	-0.03%	-0.50%
ENT	372.5	380.7	-0.01%	-0.11%	-0.07%	-0.27%	-0.07%	-1.23%
ACC	1472.5	1504.1	-0.01%	-0.06%	-0.04%	-0.13%	-0.04%	-0.64%
OG&S	1335.2	1364.2	-0.01%	-0.08%	-0.05%	-0.18%	-0.05%	-0.86%

In the longer term (i.e., up to 2150), there is a substantial difference in value of sector-specific output by climate change scenario compared to the baseline (Table 2.7). The S-FOR sector experiences a decrease in value of output across all climate change scenarios (RCP 2.6: -5%; RCP 4.5: -12%; RCP 8.5: -58%). The H-FOR sector also experiences a decrease in the value of output under all climate change scenarios (RCP 2.6: -1%; RCP 4.5: -4%, RCP 8.5: -17%). Interestingly, the H-FOR sector experiences a decrease in value of output under RCP 2.6 and RCP 8.5 even though there is an increase in the supply of hardwood stumpage in both scenarios. This reduction in value of output from wood-related manufacturing sectors drives down the value of output from the H-FOR sector.

There are several sectors (i.e., CROP, FISH, OILGAS, OTH-MANUF, and TRADES) that experience an increase in value of output following climate-driven changes in the supply of hardwood and softwood under all climate change scenarios relative to the baseline, with the largest increase occurring under RCP 8.5 (Table 2.7).

Imports and exports of forestry and logging and other wood-related manufacturing sectors exhibit little differences between scenarios up until 2080 (Figures 2.6 and 2.7). After 2080, imports increase under RCP 2.6, 4.5, and 8.5 by 1.55%, 3.60%, and 20.71%, respectively, by 2150 compared to the baseline. Exports, on the other hand, decrease under RCP 2.6, 4.5, and 8.5 by 2.13%, 5.04%, and 22.99%, respectively, by 2150 compared to the baseline. The change in both imports and exports is directly linked to the reduction in output of these sectors. As output decreases, other sectors are forced to import these products to meet their demand.

Additionally, as these sectors struggle to meet the domestic demand, they have less product available for export.

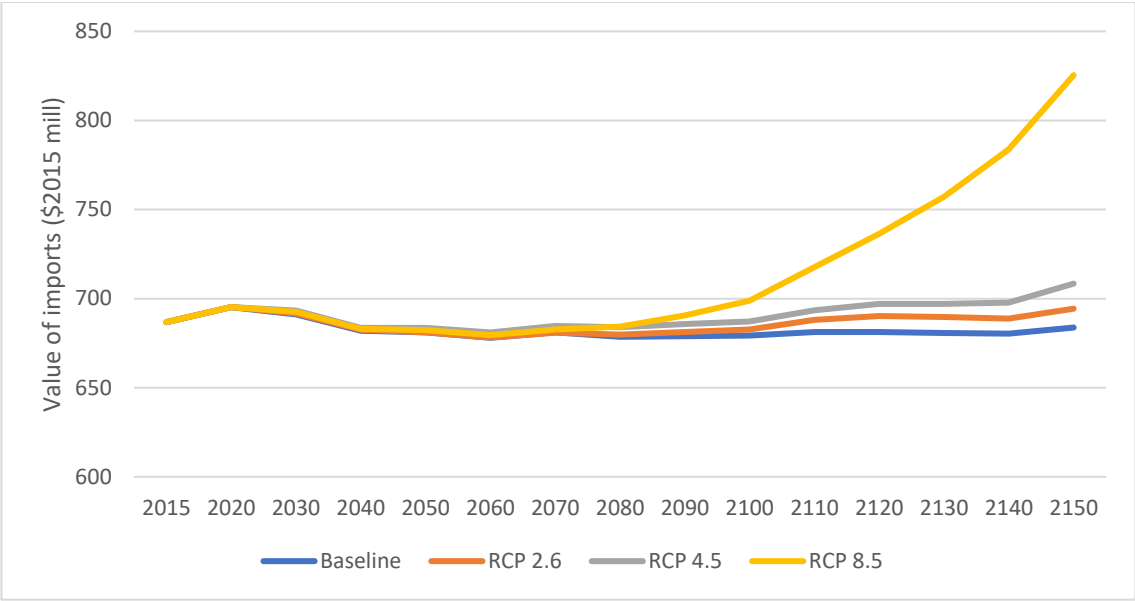

Figure 2.6 Imports of forestry and logging and wood-related manufacturing goods into New Brunswick from 2015-2150 ($2015 mill)

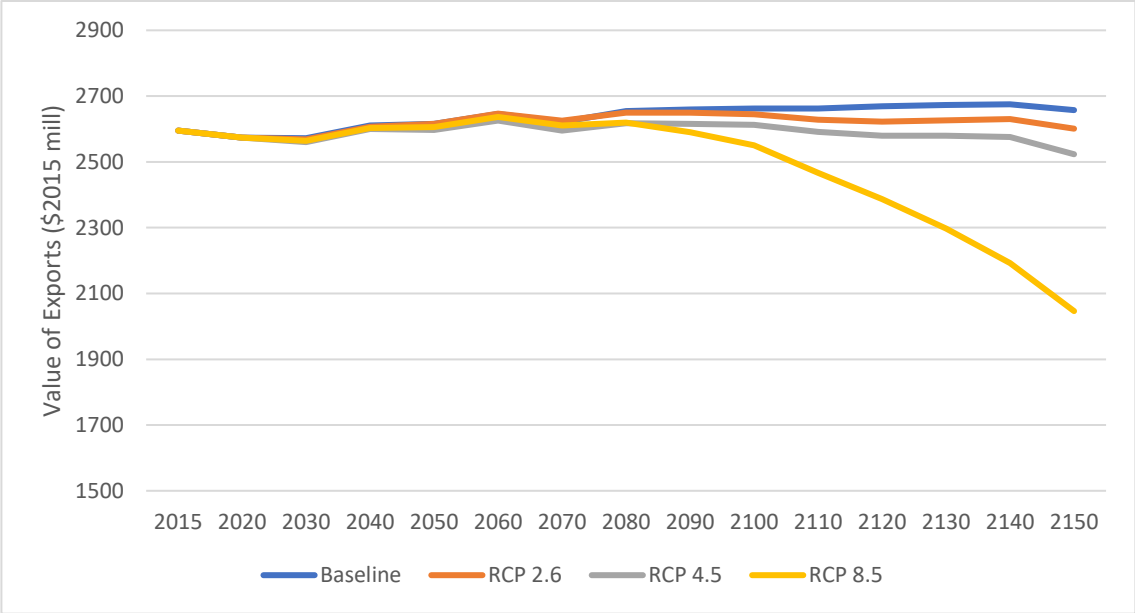

Figure 2.7 Exports of forestry and logging and wood-related manufacturing goods into New Brunswick from 2015-2150 ($2015 mill)

2.4.2.2 Macro-economic impacts

At the macro-economic level, GDP, Y, EV, C and CG all experience minor decreases in value in the short term (up to 2080) following climate-driven changes in supply of hardwood and softwood under all climate change scenarios relative to the baseline (Table 2.8). These results align with both the ecological analysis as well as the sector-specific results, as there are few differences between scenarios before 2080. In the longer term (up to 2150), these variables exhibit relatively larger decreases under the climate change scenarios relative to the baseline, with the largest decrease occurring under RCP 8.5. EV experiences the largest decrease in value out of all economy-wide indicators with a change of -0.96%, -2.28% and -11.82% under RCP 2.6, RCP 4.5, and RCP 8.5 respectively.

Table 2.8 Macro-economic variables in New Brunswick by scenario) in 2080 and 2150 (% difference from Baseline)

	Scenarios							
Variables	Baseline ($ millions)		RCP 2.6 (% diff)		RCP 4.5 (% diff)		RCP 8.5 (% diff)	
	2080	2150	2080	2150	2080	2150	2080	2150
GDP	30170	31037	-0.01%	-0.08%	-0.05%	-0.18%	-0.05%	-0.88%
Y	30295	30809	0.00%	-0.03%	-0.02%	-0.08%	-0.02%	-0.39%
EV	515	1029	-0.18%	-0.96%	-1.23%	-2.28%	-1.20%	-11.82%
C	20998	21355	0.00%	-0.03%	-0.02%	-0.08%	-0.02%	-0.39%
CG	11156	11549	0.00%	-0.01%	-0.01%	-0.02%	-0.01%	-0.11%
INV	3036	3082	0.00%	0.01%	0.00%	0.01%	0.00%	0.02%
K	9423	9597	0.00%	-0.02%	-0.01%	-0.04%	-0.01%	-0.15%
L	17755	18298	-0.01%	-0.06%	-0.06%	-0.24%	-0.06%	-1.11%
IMP	28864	29147	0.03%	0.35%	0.22%	0.83%	0.22%	4.00%
EXP	23843	24198	0.04%	0.38%	0.24%	0.90%	0.24%	4.33%
XD	52854	54242	0.01%	0.07%	0.04%	0.17%	0.04%	0.78%
XDD	29011	30044	-0.02%	-0.17%	-0.12%	-0.42%	-0.11%	-2.08%

GDP = gross domestic product; Y = household income; EV = equivalent variation; C= household consumption; CG = government consumption; INV = investment; K = capital; L = labour; IMP = value of imports; EXP = value of export; XD = domestically consumed output; XDD = domestically produced and consumed output.

Interestingly, the value of IMP, EXP, and XD increase under all climate change scenarios relative to the baseline in both the short term and long term (Table 2.8). The largest increases tend to be under the most severe (RCP 8.5) climate change scenario. The increase in imports aligns with the results seen for total imports of wood-related goods and services.

The increase in value of EXP is unexpected as it is expected to decline, following the decline in GDP (Table 2.8). However, since we specified fixed foreign savings in our model as a market closure condition, EXP are forced to increase to balance the increase in IMP.

Another unexpected finding is the increase in value of XD, which represents domestic output (i.e., domestically produced and imported goods). Similar to IMP and EXP, the largest increase in XD occurs under the most severe climate change scenario. The increase in XD is driven by the increase of IMP into the economy—as XD is a function of XDD (domestically produced and consumed output) and IMP, and the increase in IMP is larger than the decrease in XDD.

As mentioned above, XDD decreases across all scenarios with the largest decrease occurring under RCP 8.5. The reduction in value of XDD is a result of the decrease in supply of softwood, which in turn causes a decrease in the amount of domestically produced and used out–put - specifically for sectors that are highly connected to the S-FOR sector.

The variable INV also experiences a relatively minor increase across all climate change scenarios compared to the baseline, with the largest increase being 0.02% and

occurring in 2150 under RCP 8.5 (Table 2.8). The increase in investment is caused by its relationship to total savings, which tends to increase.

Finally, K and L decrease across all time horizons and climate change scenarios, with the most severe decrease in K (0.15%) and L (1.11%) taking place under RCP 8.5 (Table 2.9). The reduction in L causes an increase in the unemployment rate (Figure 2.8) under RCP 2.6 (0.72%), RCP 4.5 (1.68%) and RCP 8.5 (7.85%).

Table 2.9 Cumulative present value macro-economic variables in New Brunswick by scenario between 2015-2150 (% difference from Baseline, 2% discount rate)

Variables	Baseline ($ mill)	RCP 2.6 (% diff)	RCP 4.5 (% diff)	RCP 8.5 (% diff)
GDP	170453	-0.01%	-0.03%	-0.07%
Y	172127	0.00%	-0.01%	-0.03%
EV	1444	-0.38%	-1.30%	-2.95%
C	119306	0.00%	-0.01%	-0.03%
CG	62866	0.00%	0.00%	-0.01%
INV	17270	0.00%	0.00%	0.00%
K	53510	0.00%	-0.01%	-0.01%
L	100220	-0.01%	-0.04%	-0.08%
IMP	164993	0.04%	0.13%	0.28%
EXP	136003	0.04%	0.14%	0.31%
XD	299301	0.01%	0.03%	0.06%
XDD	150539	-0.019%	-0.07%	-0.15%

GDP = gross domestic product; Y = household income; EV = equivalent variation; C= household consumption; CG = government consumption; INV = investment; K = capital; L = labour; IMP = value of imports; EXP = value of export; XD = domestically consumed output; XDD = domestically produced and consumed output.

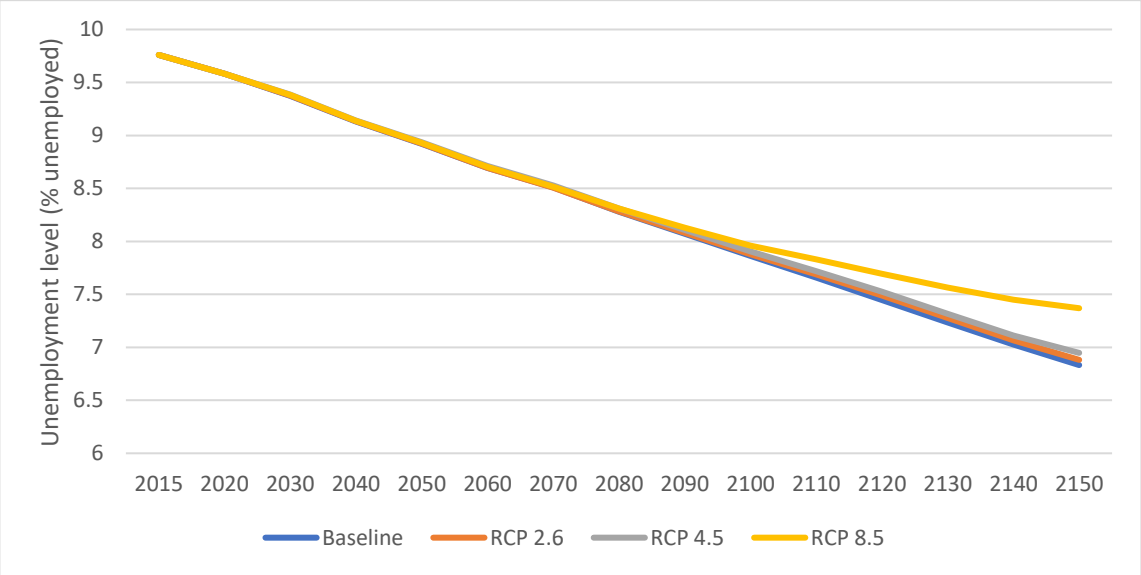

Figure 2.8 Unemployment rate in New Brunswick by scenario between 2015 and 2150 (% unemployed)

The cumulative economic impacts of the climate change scenarios compared to the baseline are relatively small across all climate change scenarios (Table 2.9). Here, the largest reduction is EV, which experiences a change of -0.38%, -1.30% and -2.95% under RCP 2.6, RCP 4.5, and RCP 8.5, respectively.

2.5 Discussion

2.5.1 Climate change impacts on the forest landscape

In this study, we conduct a long-term ecological and economic analysis of the impact of climate change on the forest of New Brunswick, Canada, using a PICUS-LANDIS-CGE modeling framework. This represents the first study that has coupled such a forest landscape modeling framework with a CGE model.

The results show that climate change could cause a relatively large reduction in softwood supply (ranging between 9-26%) and a smaller change in hardwood supply (ranging from -2% to 4%) by 2150. The reduction in biomass harvested of softwood is the result of increasing temperature and drought-like conditions negatively impacting the fitness of cold-adapted softwood tree species (Reich et al. 2015, Fisichelli et al. 2014). Additionally, changes in climate increase the competitiveness of thermophilic hardwood tree species, which allows them to outcompete dominant softwood tree species for scarce resources. Although some hardwood species gain a competitive advantage, it does not necessarily translate to a significant increase in biomass harvested. This is partially caused by dispersal limitations, as hardwood species are unable to fully establish in areas still occupied by poorly performing cold adapted

softwood species, especially in the northern part of the province. This is also referred to as the “blocking effect” (Taylor et al., 2017), as established cold adapted boreal species “block” the growth of warm adapted species through appropriating resources (light, water, nutrients). This process creates a lag (Bertrand et al., 2011; Zhu et al., 2014) in the growth of warm adapted species, with the effect being felt for the next 50-150 years. The ending of the blocking effect is likely an uptick in supply of hardwood to the economy in RCP 4.5 and RCP 8.5 (Figure 2.3).

2.5.2 Impacts on wood supply and forestry sectors

As seen in the results, the change in wood supply is felt most within the forestry and logging and wood-related manufacturing sectors. The S-FOR sector could experience a decrease in the value of output between 5% and 58%, while the H-FOR sector could experience a range of impacts between -1% to +17% by 2150. Wood-related manufacturing sectors could also experience a decrease in output under all climate change scenarios, with the veneer wood manufacturing sector consistently experiencing the largest decrease at up to 53% in 2150. This aligns with what would be expected as this sector requires the largest amount of S-FOR intermediate outputs compared to the other wood-related manufacturing sectors (Table 2.3). Interestingly the results highlight how a change in value of output from the H-FOR sector only has a minor influence over other sectors variables (e.g., output quantity, price, and output value). This is likely a result of the H-FOR sector being significantly smaller than the S-FOR sector. For instance, in 2015, New Brunswick hardwood accounts for less than 35%

of total wood harvested (CCFM, 2020a). Furthermore, the intermediate demand for hardwood output is overshadowed by the demand of intermediate softwood output (Table 3). As such, a reduction in supply of softwood results in softwood goods acting as a limiting factor for wood related manufacturing sectors, which causes these sectors to be unable to take advantage of the increase in output from the H-FOR sector.

Although this is the first study to join a CGE model with a PICUS-LANDIS framework, it is interesting to examine how the sectoral results align with other studies that have investigated how a climate induced change in wood supply would impact the New Brunswick economy. For instance, Ochuodho & Lantz (2014) use a single regional CGE model and estimate that there would be little to no change in cumulative (4% discount rate) economic output by the forestry and logging sector under severe climate change by 2051. The differences in findings between Ochuodho & Lantz (2014) and this study is the result of both the differences in CGE model structure (i.e. aggregated wood supply vs disaggregated wood supply) as well as how wood supply is determined. For instance, Ochuodho & Lantz (2014) use peer reviewed data along with expert opinion, while the current study uses an ecological model.

Meanwhile Lantz et al. (2022) uses a similar CGE model to ours, joined with a forest management model to estimate a 12.94% and 7.20% reduction in output quantity from the S-FOR and H-FOR sectors, respectively, by 2095 under RCP 8.5. In comparison, we estimate a 9.22% and a 3.25% reduction in value of output from the S-FOR and H-FOR sectors, respectively, under RCP 8.5. The differences in findings between these two studies are mainly a result of differences in how wood supply was

modeled. Specifically, while Lantz et al. (2022) project significant wood supply impacts starting in 2025, our study projects these impacts starting much later in 2080 (Figure 2.2, and 2.3), which receives less value due to discounting. Since the approach in this study focuses moreso on modeling ecological processes, we contend that our estimates are more robust than Lantz et al. (2022).

2.5.3 Impacts on the macro-economy

The relatively large impacts of climate change in the forestry and wood-related sectors lead to smaller climate change impacts on macro-economic variables (GDP, Y, XD, etc.), which generally change by less than 1% relative to the baseline. The relatively small economic impact estimates on the economy in the short term, long term and cumulatively is due to a combination of factors. For instance, in the short term, there is little to no change in the economic indicators between scenarios. The main reason for this is climate change does not have a significant impact on the quantity and composition of New Brunswick's wood supply before 2080. This aligns with recent studies (e.g., Boulanger et al., 2018; Brecka et al., 2020; Girardin, Hogg, et al., 2016) that suggest that the impact of a changing environment is not truly felt within the forest until the latter half of the 21st century.

The relatively small macro-economic impacts that have emerged from climate change over the long term in this study are likely an underestimate of the impact a change in quality and composition will have on the economy. The underestimated is likely the result of several sectors (i.e., CROP, FISH, OILGAS) experiencing an increase in

value of output under climate change, with the largest increase in value occurring under RCP 8.5. This occurs due to the redistribution of capital within the economy, which is the result of the forestry and wood related sectors requiring less factors of production due to reduction in supply of softwood and the need for the capital market to be cleared at the end of each period. Furthermore, there is a second group of sectors (i.e., OTH-MANUF and TRADES) experience an increase in output due a trickle-down effect caused by the high degree of connectivity with the first group through demand for intermediate goods. However, in reality the first group of sectors will sectors will likely not be able to increase their output as climate change and climate policy may restrict their ability to access the natural capital (e.g., farm land, fish stocks, oil, gas and minerals) that they rely on (Allison et al., 2009; Fezzi & Bateman, 2015; Mu et al., 2013).

The timing of wood supply changes combined with the time value of money is yet a further factor contributing to the relatively small cumulative macro-economic impacts resulting from each climate change scenario. Specifically, as explained previously, we find that climate change does not have a significant impact on the quantity and composition of New Brunswick's wood supply until approximately 2080. Since the cumulative economic impact values are calculated in present value terms, the results that are most impacted by climate change are also the ones that are discounted the most. As with the use of the 2% discount rate, variables after 2080 are highly discounted. It is important to note that the impact in both the macro-economic, and the cumulative macro-economic variables will likely be felt disproportionately by the 12

forest dependent communities within the province (Statistics Canada, 2018a). As such these communities will almost certainly experience an economic downturn that is substantially greater than the rest of the economy.

While the GDP impact findings of this study are not directly comparable to those of previous studies due to the different regions, climate change, and socio-economic scenarios considered, it is of interest to consider how they compare with the literature. In general, we find that our estimates fall within the range of similar studies. For instance, while we find cumulative present value GDP losses of between $17 million (-0.01%) to $119 million (-0.07%) over 2015-2150 using a 2% discount rate in New Brunswick, Ochuodho et al. (2012) find losses ranging from $80 million to $14 billion over 2010-2080 using a 3% discount rate for the entire Atlantic Canadian region (including New Brunswick, Nova Scotia, PEI, and Newfoundland & Labrador). Additionally, Boccanfuso et al. (2018) find current value GDP losses of 0.12% by 2050 in Quebec by 2050, representing approximately $300 million. Given that Quebec has a larger economy and forestry sector, our GDP estimates can generally be said to fall within those published in past literature. Recently, however, Lantz et al. (2022) use a CGE model inconjuction with a forest management model (i.e., Woodstock) calibrated to Crownland forests to model wood supply under variouse climate adapated plans. They estimate cumulative present value GDP losses of up to $240 million (-0.08%) over 2015-95 using a 2% discount rate in New Brunswick, which is roughly double the highest range finding in the current study. The differences largly have to due with how each model represents ecolgoical processes in addation to how management actitivies

(harvesting rates) are simulated. These differences result in Lantz et al. (2022) predicting earlier climate change impacts on wood supply and their associated values, as previously explained.

2.5.4 Limitations

There are several limitations associated with the models used in our analysis that may introduce bias into the findings. For instance, our analysis does not consider possible impacts of climate change on other forms of capital including natural capital and infrastructure (e.g., transportation networks and energy grids) which will likely be negativity impacted by climate change. Taking these factors into account might increase the scale of negative economic impacts of climate change considered here.

Secondly, our PICUS-LANDIS framework does not account for how climate change directly impacts some ecological drivers within the forest (e.g., pest outbreaks and windthrow) as well as CO_2 fertilization effects (e.g., elevated CO_2 levels and longer growing seasons may increase growth rates of individual tree species (Price et al., 2013). For instance, we assume SBW outbreaks are not directly influenced by climate change. However, these assumptions likely only have a marginal impact on biomass accumulation, species composition and ultimately harvested biomass and composition over time. This is due to studies suggesting that any gain in biomass associated with the reduced outbreak severity of this pest (Gray, 2008, 2013; Régnière et al., 2012) could be offset by an increased prominence of other pests that are currently limited by cold weather such as hemlock woolly adelgid (*Adelges tsugae*, Paradis et al., 2008).

Furthermore, the increase in growth rates due to CO_2 fertilization has historically been minor and will likely only have a minor impact on future forest growth in Canada (Girardin et al., 2016).

Thirdly, while other studies (e.g. Maclean et al., 2022; Taylor et al., 2017) that examine the impact climate change will have on the forest landscape of Atlantic Canada include windthrow as a disturbance, ours does not account for this. Windthrow events would likely result in an increase in open canopy which could accelerate the conization of warm adapted hardwood species and reduce the length of the blocking effect (Boulanger et al., 2019). However, windthrow events would likely only have a marginal impact on the length of the blocking effect, especially in the western parts of New Brunswick, where other disturbances (most noticeably SBW outbreaks) play a more significant role in defining the forest landscape (Boulanger et al., 2012).

Fourthly, as our study focus is on climate change, we do not consider different forest management and/or adaptation scenarios. Specifically, the harvesting scenarios we use does not maximize the amount of wood harvested nor does it assume a preference between hardwood and softwood species. A harvesting scheme that favors one type of species (e.g., softwood) would likely result in an initial steady increase in biomass of that species harvested in the short term. However, as that species becomes depleted due to selective harvesting and possible climate change mortality increases, there would be a significant reduction in supply of that species in future years, unless silvicultural interventions were to be implemented. Recently, Lantz et al. (2022), as described previously, join a forest management (i.e., Woodstock) model with a CGE

model to examine possible silvicultural adaptation strategies for Crownland forests in New Brunswick. The two strategies that were tested included planting genetically modified softwood species or replacing failed softwood plantations with warm adapted hardwood plantations. This study provide insight into the benefit of potential mitigation strategies on Crownland, with the results highlighting the importance of appropriate management of Crownland softwood plantations. It would be of interest to explore these and other forest management and/or adaptation strategies in our modeling environment in the future.

Fifthly, our analysis could also be refined by distinguishing between Crownland vs private forests and considering their unique management regimes. This is an important factor in New Brunswick since each group manages about 50% of forestland in the province, and prescribe varying forest management practices. Furthermore, stumpage rates can vary between Crownland Forests and Private Forests even though the Crownland stumpage rate are based off the free market (NBFPC, 2016). Recent audits of the forestry and logging sector have suggested that it can take up to four years for Crownland stumpage rates adjust to a change in Private stumpage rates (Auditor General of New Brunswick, 2020). This lag effect could impact the provincial economy as wood supplied from Crownland would either be overvalued or undervalued depending on when Crownland stumpage prices are set.

Sixthly, the elasticity parameters used when calibrating our CGE model were collected from peer reviewed literature across North America. These estimates are likely to change over time as agents' (producers, government, and households)

technologies and/or preferences for goods and services evolve. Additionally, these estimates may not reflect the true technologies and preferences of the case study region considered in this study. Future research should be directed toward estimating these parameters for the region in order to reduce potential bias in the findings. This includes determining the elasticity of substitution between hardwood and softwood; although each type of wood has unique characteristics and properties there is likely a degree of substitutions between them, especially as an intermediate good.

Finally, it is important to recognize that our analysis does not disaggregate the supply of hardwood and softwood into various products (e.g., logs and bolts, pulpwood, and fuelwood) or grades of wood. These specifications can have a significant influence on the value of wood harvested, as they dictate what the wood can be used for. For instance, sawmills and wood preservation manufacturing and veneer and plywood manufacturing rely heavily on high quality logs and bolts while pulp paper and carboard manufacturing can accept relatively lower quality pulpwood. Climate change can also alter the quality of wood that is grown and harvested (Wood et al., 2016), which can also affect the product type, grade and ultimately value of wood. It would be of interest to investigate the extent to which these and other factors described above can affect the economic impact estimates in our analysis.

2.5.5 Implications of the study

It is widely acknowledged that climate change will alter forests around the world through regional changes in temperature, precipitation, and natural

disturbances. In the case study region of New Brunswick, where the Acadian Forest is both culturally and economically significant, the impact of climate driven change to characteristics of the current forest landscape has been well studied (e.g., Boulanger et al., 2017, 2018; Bourque & Hassan, 2008; Brecka et al., 2020; Taylor et al., 2017; Vaughn et al., 2021). These studies highlight how climate driven changes will have a negative impact on both stand and landscape-level dynamics, which in turn result in a significant change to the structure and composition of the forest. Yet, economic studies (e.g Ochuodho et al., 2012; Ochuodho et al., 2016) have oversimplified these changes in forest stand and landscape-level dynamics as they fail to distinguish between hardwood and softwood, let alone the individual species.

We address this oversimplification by establishing a new framework which, notwithstanding the limitations mentioned in the discussion section, contends that the estimates produced in this study are generally more robust than previous CGE studies because: (i) our future forest scenarios are designed using an ecological model (i.e., the PICUS-LANDIS framework) rather than using a range of estimates drawn from previous literature, or a forest management model with a less rigorous focus on ecological processes; and (ii) we account for unique changes in softwood vs hardwood wood supplies in our CGE model, which we demonstrated will be uniquely affected by climate change.

The methodology advances will allow researchers and policy makers to develop more complex mitigation strategies that lower the economic impact associated with climate change altering the forest structure. The mitigation strategies can incorporate

both forest management strategy that aims at reducing the reduction in biomass harvested of cold adapted softwood species (e.g., balsam fir, black spruce, and white spruce) in conjunction with economic polices that stimulates the growth of sectors (e.g., PUP-MANUF) that are able to take advance of the increase supply of hardwood from warm adapted species (e.g., red maple, yellow birch and American beech).

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2.7 Appendix

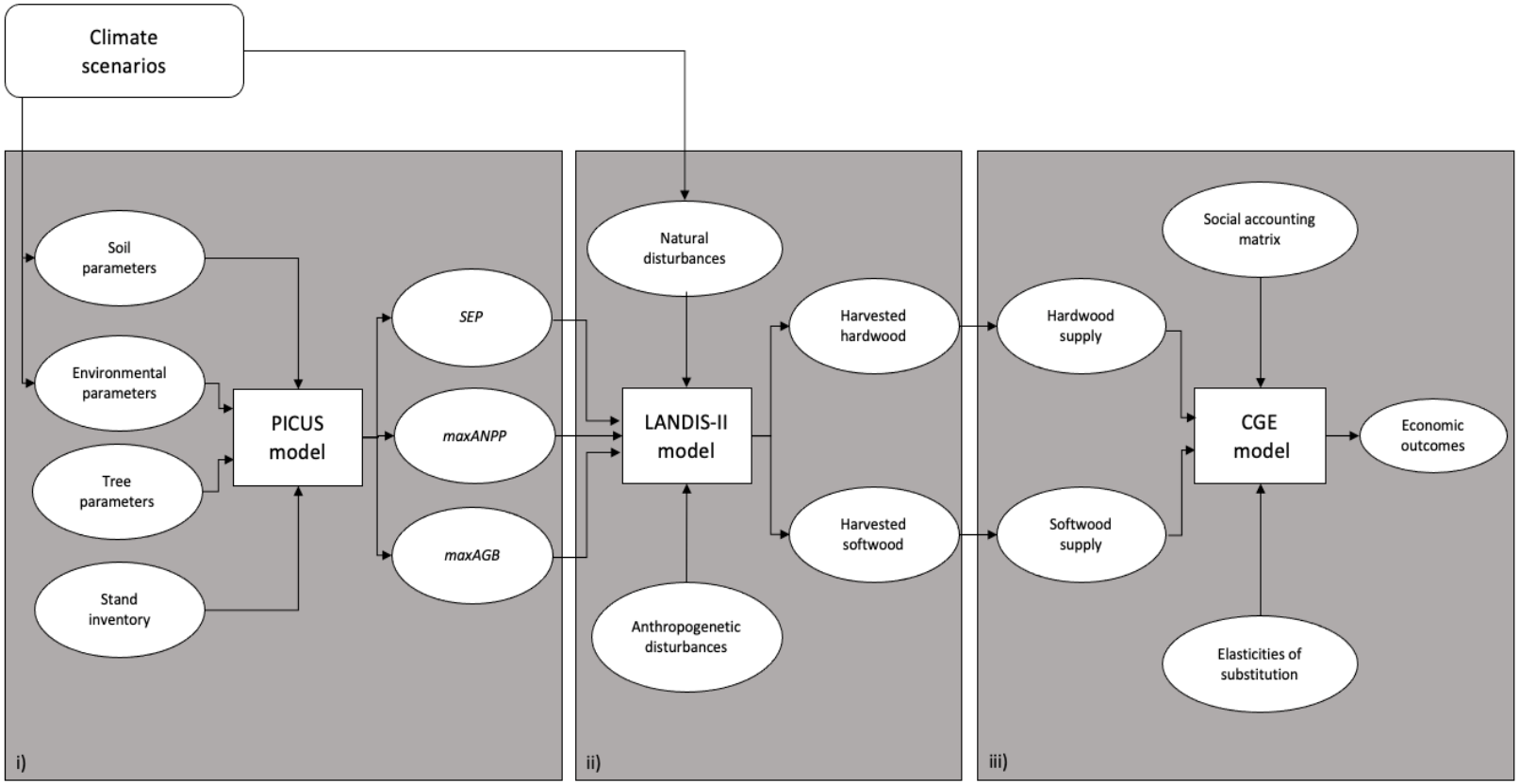

Figure A1 Visualization of the joining of PICUS(i), LANDIS-II(ii), and the CGE (iii) model

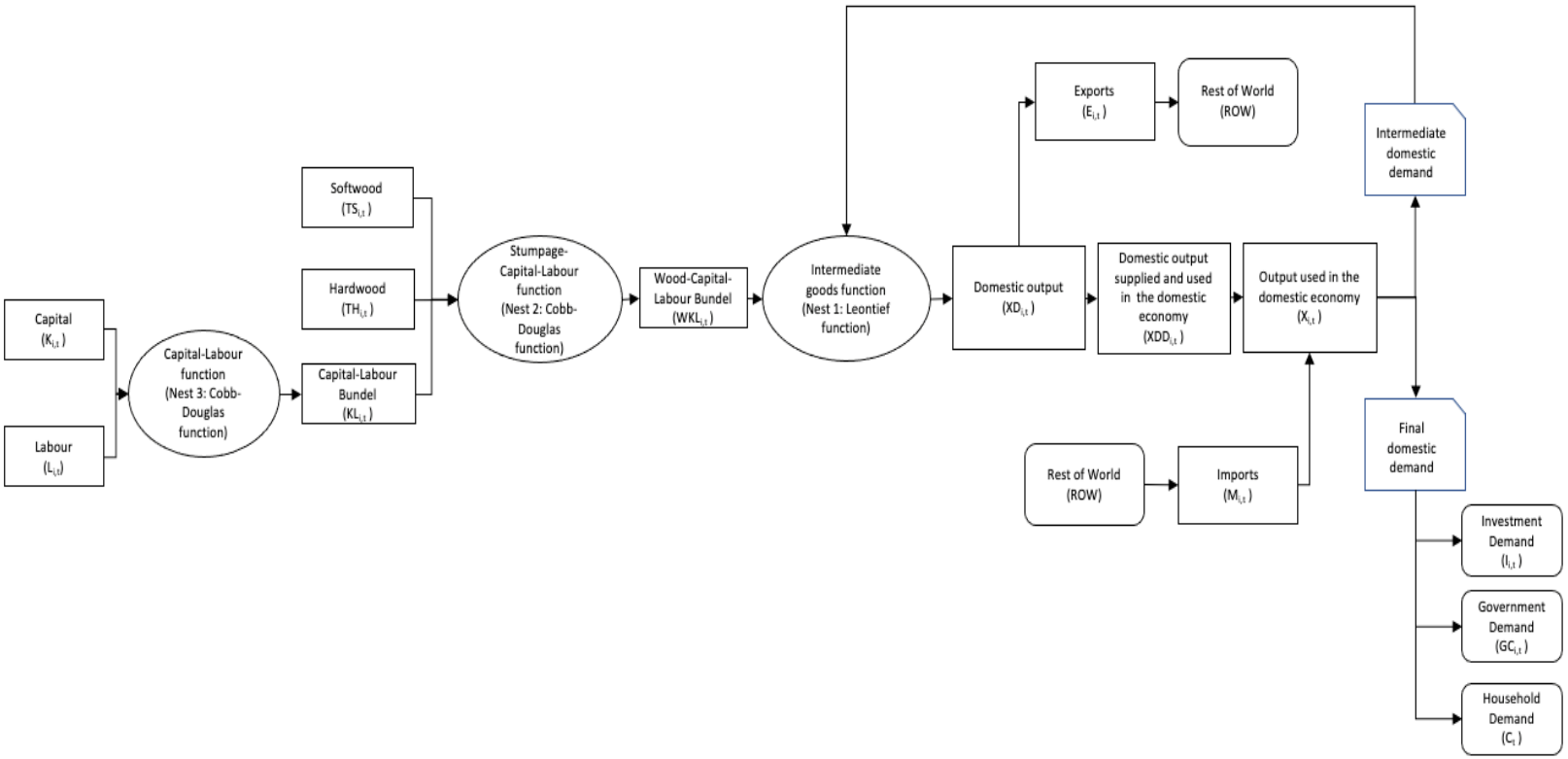

Figure A2 Structure of the four factor CGE model used within the study

Table A1 Parameters used within the CGE model

Parameters	Discerption
Elasticities	
$\boldsymbol{\sigma F2_i}$	Substitution between factors (capital-labour bundle, hardwood stumpage, and softwood stumpage) within the second nest of the production function
$\boldsymbol{\sigma F3_i}$	Substitution between factors (capital and labour) within the third nest of the production function
$\boldsymbol{\sigma T_i}$	CET substitution between domestic market and the export market
$\boldsymbol{\sigma A_i}$	Arrington substation between domestic commodities and imported commodities
Share parameters	
$\boldsymbol{\gamma KL2_i}$	Share parameter for capital-labour bundle in the second nest of the production function
$\boldsymbol{\gamma TH2_i}$	Share parameter for hardwood stumpage in the second nest of the production function
$\boldsymbol{\gamma TS2_i}$	Share parameter for softwood stumpage in the second nest of the production function
$\boldsymbol{\gamma F3_i}$	Share parameter for the third nest of the production function the third nest
$\boldsymbol{\gamma T_i}$	Share parameter of the CET function and the destination of domestically produced commodities
$\boldsymbol{\gamma A_i}$	Share parameter of the Arrington function
Efficiency parameters	
$\boldsymbol{\lambda F1_i}$	Efficiency parameter for the factors of production (stumpage-capital-labour) in the first nest of the production function.
$\boldsymbol{\lambda F2_i}$	Efficiency parameter for the factors of production (capital-labour bundle, hardwood stumpage, and softwood stumpage) in the second nest of the production function.
$\boldsymbol{\lambda F3_i}$	Efficiency parameter for the factors of production (capital and labour) in the third nest of the production function.
$\boldsymbol{\lambda A_i}$	efficiency parameter in the Arrington function
$\boldsymbol{\lambda T_i}$	Shift parameter in the CET function
Tax rates	
tc_i	Tax rate on commodities consumed by the households
tk_i	Tax rate on capital
tl_i	Tax rate on labour
tY	Tax rate on household income
Tm_i	Tariff rate on imported commodities
Others	
$\boldsymbol{\alpha HLES_i}$	Power in the nested ELES household utility function
$\boldsymbol{\alpha KG}$	Cobb-Douglass power in the government's capital demand function
$\boldsymbol{\alpha LG}$	Cobb-Douglass power in the government's labour demand function
$\boldsymbol{\alpha CG_i}$	Cobb-Douglass power in the government's commodity demand function
$\boldsymbol{\alpha I_i}$	Cobb-Douglass power in the bank's commodity demand function
trep	Replacement rate
$io_{i,j}$	Technical coefficient of intermediate input
$\boldsymbol{\varphi}$	Philips curve parameter
$\boldsymbol{\mu H}$	Households' subsistence consumption level
mps	Households' marginal propensity to save
Growth rates	
GRL	Growth rate of labour
$\boldsymbol{\psi}$	Initial real rate of return

Table A2 Variables used within the CGE model

Variables	Description
Production block	
$WKL_{i,t}$	Stumpage-capital-labour bundle
$KL_{i,t}$	Capital-labour bundle
$TH_{i,t}$	Hardwood demand
$TS_{i,t}$	Softwood demand
$K_{i,t}$	Capital demand
$L_{i,t}$	Labour demand
$X_{i,t}$	Domestic sales of composition commodities
$XD_{i,t}$	Domestically produced commodities (outputs)
$XDD_{i,t}$	Domestically produced commodities sold to the domestic market
$PWKL_{i,t}$	Price of stumpage-capital-labour bundle
$PKL_{i,t}$	Price of capital-labour bundle
PTH_t	Price of hardwood stumpage
PK_t	Price of capital (Rent)
PL_t	Price of labour (wages)
$P_{i,t}$	Price of composition commodities sold in
$PD_{i,t}$	Price of domestically produced commodities
$PD_{i,t}$	Price of domestically produced commodities
$PDD_{i,t}$	Price of commodities sold to the domestic market
$PD_{i,t}$	Price of domestically produced commodities
Household block	
Y_t	Household's income
$CBUD_t$	Household's expenditure
C_t	Household's demand for commodities
$PCINDEX_t$	Consumer price index
Factor supply	
LS_t	Labour supply (endowment)
KS_t	Capital supply (endowment)
TSS_t	Softwood stumpage supply (endowment)
THS_t	Hardwood stumpage supply (endowment)

Variables	Description
Investment block	
S_t	Total saving
SF_t	Forging savings
SG_t	Government's savings
$I_{i,t}$	Investment demand
Trade block	
$E_{i,t}$	exports of commodities
$M_{i,t}$	Imports of commodities
$PE_{i,t}$	Domestic price of exports
$PM_{i,t}$	Domestic price of imports
ER_t	Exchange rate
Government block	
LG_t	Government's demand for labour
KG_t	Government's demand for capital
$GC_{i,t}$	Government's demand for commodities
$TAXR_t$	Total taxes
TRF_t	Total transfer from the government to the household
TRO_t	Other transfers from the government to the household
$UNEMP_t$	economy wide unemployment
Dynamic Variables	
$GRSS_t$	Growth rate of softwood stumpage
$GRHS_t$	Growth rate of hardwood stumpage
RRR_t	Real rate of return

Table A3 Equations used in the CGE model

Equations		Description
Production block		
$\mathbf{WKL_{i,t} = \lambda F1_i * XD_{i,t}}$	EQ 1.1	Firms' demand for wood-capital-labour bundle (1st nest)
$\boldsymbol{PD_{i,t} * XD_{i,t} = (PWKL_{i,t} * WKL_{i,t}) + \left(\sum_j io_{j,i} * XD_{i,t} * P_{i,t}\right)}$	EQ 1.2	Firms' zero profit condition (1st nest)
$\mathbf{KL_{i,t}} = \frac{\mathbf{WKL_{i,t}}}{\mathbf{\lambda F2_i}} * \left(\frac{\boldsymbol{\gamma KL2_i}}{\boldsymbol{PKL_{i,t}}}\right)^{\boldsymbol{\sigma F2_i}} * \left[\left(\boldsymbol{\gamma KL_i^{\sigma F2_i} * PKL_{i,t}^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TS_i^{\sigma F2} * PTS_t^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TH_i^{\sigma F2} * PTH_t^{(1-\sigma F2_i)}}\right)\right]^{\left(\frac{\boldsymbol{\sigma F2_i}}{(\boldsymbol{1-\sigma F2_i})}\right)}$	EQ 1.3	Firms' demand for capital-labour bundle
$\mathbf{TH_{i,t}} = \frac{\mathbf{WKL_{i,t}}}{\mathbf{\lambda F2_i}} * \left(\frac{\boldsymbol{\gamma TH2_i}}{\boldsymbol{PTH_t}}\right)^{\boldsymbol{\sigma F2_i}} * \left[\left(\boldsymbol{\gamma K_i^{\sigma F2_i} * PKL_{i,t}^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TS_i^{\sigma F2} * PTS_t^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TH_i^{\sigma F2} * PTH_t^{(1-\sigma F2_i)}}\right)\right]^{\left(\frac{\boldsymbol{\sigma F2_i}}{(\boldsymbol{1-\sigma F2_i})}\right)}$	EQ 1.4	Firms' demand for hardwood (2nd nest)
$\mathbf{TS_{i,t}} = \frac{\mathbf{WKL_{i,t}}}{\mathbf{\lambda F2_i}} * \left(\frac{\boldsymbol{\gamma TS2_i}}{\boldsymbol{PTS_t}}\right)^{\boldsymbol{\sigma F2_i}} * \left[\left(\boldsymbol{\gamma KL_i^{\sigma F2_i} * PKL_{i,t}^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TS_i^{\sigma F2} * PTS_t^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TH_i^{\sigma F2} * PTH_t^{(1-\sigma F2_i)}}\right)\right]^{\left(\frac{\boldsymbol{\sigma F2_i}}{(\boldsymbol{1-\sigma F2_i})}\right)}$	EQ 1.5	Firms' demand for softwood (2nd nest)
$\mathbf{PWKL_{i,t} * WKL_{i,t}} = \left(\boldsymbol{(PKL_{i,t} * KL_{i,t}) + (PTH_t * TH_{i,t}) + (PTS_t * TS_{i,t})}\right)$	EQ 1.6	Firms' zero profit condition (2nd nest)

$\mathbf{K_{i,t}} = \frac{\mathbf{KL_{i,t}}}{\boldsymbol{\lambda}\mathbf{F3_i}} * \left(\frac{\boldsymbol{\gamma F3_i}}{(\mathbf{1}+\boldsymbol{tk_i}) * \boldsymbol{PK_t}}\right)^{\boldsymbol{\sigma F3_i}} * \left[\left(\boldsymbol{\gamma F3_i^{\sigma F3_i}} * \left((\mathbf{1}+\boldsymbol{tk_i}) * \boldsymbol{PK_t}\right)^{(\mathbf{1}-\boldsymbol{\sigma F3_i})}\right) + \left((\mathbf{1}-\boldsymbol{\gamma F3_i})^{\boldsymbol{\sigma F3_i}} * \left((\mathbf{1}+\boldsymbol{tl_i}) * \boldsymbol{PL_t}\right)^{(\mathbf{1}-\boldsymbol{\sigma F3_i})}\right)\right]^{\left(\frac{\boldsymbol{\sigma F2_i}}{(\mathbf{1}-\boldsymbol{\sigma F2_i})}\right)}$	EQ 1.7	Firms' demand for capital (3rd nest)
$\mathbf{L_{i,t}} = \frac{\mathbf{KL_{i,t}}}{\boldsymbol{\lambda}\mathbf{F3_i}} * \left(\frac{(\mathbf{1}-\boldsymbol{\gamma F3_i})}{(\mathbf{1}+\boldsymbol{tl_i}) * \boldsymbol{PL_t}}\right)^{\boldsymbol{\sigma F3}} * \left[\left(\boldsymbol{\gamma F3_i^{\sigma F3_i}} * \left((\mathbf{1}+\boldsymbol{tk_i}) * \boldsymbol{PK_t}\right)^{(\mathbf{1}-\boldsymbol{\sigma F3_i})}\right) + \left((\mathbf{1}-\boldsymbol{\gamma F3_i})^{\boldsymbol{\sigma F3_i}} * \left((\mathbf{1}+\boldsymbol{tl_i}) * \boldsymbol{PL_t}\right)^{(\mathbf{1}-\boldsymbol{\sigma F3_i})}\right)\right]^{\left(\frac{\boldsymbol{\sigma F2_i}}{(\mathbf{1}-\boldsymbol{\sigma F2_i})}\right)}$	EQ 1.8	Firms' demand for labour (3rd nest)
$\boldsymbol{PKL_{i,t}} * \boldsymbol{KL_{i,t}} = \left((\mathbf{1}+\boldsymbol{tk_i}) * \boldsymbol{PK_t} * \boldsymbol{K_{i,t}}\right) + \left((\mathbf{1}+\boldsymbol{tl_i}) * \boldsymbol{PL_t} * \boldsymbol{L_{i,t}}\right)$	EQ 1.9	Firms' zero profit condition (3rd nest)
Household block		
$\boldsymbol{Y_t} = \boldsymbol{PK_t} * \boldsymbol{KS_t} + \boldsymbol{PL_t} * (\boldsymbol{LS_t} - \boldsymbol{UNEMP_t}) + \boldsymbol{TSS_t} * \boldsymbol{PTS_t} + \boldsymbol{THS_t} * \boldsymbol{PTH_t} + \boldsymbol{TRF_t}$	EQ 2.1	Household's income
$\boldsymbol{SH_t} = \boldsymbol{mps} * (\boldsymbol{Y_t} - \boldsymbol{ty} * \boldsymbol{Y_t})$	EQ 2.2	Household's saving
$\boldsymbol{CBUD_t} = (\mathbf{1}-\boldsymbol{ty}) * \boldsymbol{Y_t} - \boldsymbol{SH_t}$	EQ 2.3	Household's consumption expenditure
$(\mathbf{1}+\boldsymbol{tc_i}) * \boldsymbol{P_{i,t}} * \boldsymbol{C_{i,t}} = (\mathbf{1}+\boldsymbol{tc_i}) * \boldsymbol{P_{i,t}} * \boldsymbol{\mu H_i} + \boldsymbol{\alpha HLES_i} * (\boldsymbol{CBUD_t} - \sum_{j} (\boldsymbol{\mu H_j} * (\mathbf{1}+\boldsymbol{tc_j}) * \boldsymbol{P_{j,t}})$	EQ 2.4	Households' demand for commodities
$\left(\frac{\left(\frac{\boldsymbol{PL_t}}{\boldsymbol{PCINDEX_t}}\right)}{\left(\frac{\boldsymbol{PL_0}}{\boldsymbol{PCINDEX_0}}\right)}\right) = \boldsymbol{\varphi} * \left(\frac{\frac{\boldsymbol{UNEMP_t}}{\boldsymbol{LS_t}}}{\frac{\boldsymbol{UNEMP_0}}{\boldsymbol{LS_0}}} - \mathbf{1}\right)$	EQ 2.5	Philips wage curve

$PCINDEX_t = \frac{\left(\sum_i \left((1+tc_i) * P_{i,t} * C_{i,0}\right)\right)}{\left(\sum_i \left((1+tc_i) * P_{i,0} * C_{i,0}\right)\right)}$	EQ 2.6	Consumer price index
Saving and investment block		
$S_t = SH_t + PCINDEX_t * SG_t + SF_t * ER_t$	EQ 3.1	Total savings
$P_{i,t} * I_{i,t} = \alpha I_i * S_t$	EQ 3.2	Demand for investment
Government block		
$P_{i,t} * CG_i = \alpha CG_i * (TAXR_t - TRF_t - SG_t * PCINDEX_t)$	EQ 4.1	Government's demand for consumption
$PK_t * KG_t = \alpha KG * (TAXR_t - TRF_t - SG_t * PCINDEX_t)$	EQ 4.2	Government's demand for capital
$PL_t * LG_t = \alpha LG * (TAXR_t - TRF_t - SG_t * PCINDEX_t)$	EQ 4.3	Government's demand for labour
$TAXR_t = ty * Y_t + \sum_i ((P_{i,t} * tc_i * C_{i,t}) + (PK_t * tk_i * K_{i,t}) + (PL_t * tl_i * L_{i,t}) + (tm_i * M_{i,t} * PWM_{i,t} * ER_t))$	EQ 4.4	Government's revenue (total taxes)
$TRF_t = trep * PL_t * UNEMP_t + TRO_t * PCINDEX_t$	EQ 4.5	Total transfers from the government to the household
International trade		
$E_{i,t} = \frac{XD_{i,t}}{\lambda T_i} * \left(\frac{\gamma T_i}{PE_{i,t}}\right)^{\sigma T_i} * \left(\left(\gamma T_i^{\sigma T_i}\right) * \left(PE_{i,t}^{(1-\sigma T_i)}\right) + \left((1-\gamma T_i)^{\sigma T_i} * \left(PDD_{i,t}^{(1-\sigma T_i)}\right)\right)\right)^{\frac{\sigma T_i}{1-\sigma T_i}}$	EQ 5.1	CET function for selling output to the international market

$XDD_{i,t} = \frac{XD_{i,t}}{\lambda T_i} * \left(\frac{(1-\gamma T_i)}{PDD_i, t}\right)^{\sigma T_i} * \left(\left(\gamma\, T_i^{\sigma T_i}\right) * \left(PE_{i,t}^{(1-\sigma T_i)}\right) + \left((1-\gamma T_i)^{\sigma T_i} * \left(PDD_{i,t}^{(1-\sigma T_i)}\right)\right)\right)^{\frac{\sigma T_i}{1-\sigma T_i}}$	EQ 5.2	CET function for selling output to the domestic market
$PD_{i,t} * XD_{i,t} = PE_i * E_{i,t} + PDD_{i,t} * XDD_{i,t}$	EQ 5.3	Zero profit condition for the CET function
$M_{i,t} = \frac{X_{i,t}}{\lambda A_i} * \left(\frac{\gamma A_i}{PM_{i,t}}\right)^{\sigma A_i} * \left(\left(\left(\gamma A_i^{\sigma A_i}\right) * \left(PM_{i,t}^{(1-\sigma A_i)}\right)\right) + \left((1-\gamma A_i)^{\sigma A_i} * \left(PDD_{i,t}^{(1-sigmaA_i)}\right)\right)\right)^{\frac{\sigma A_i}{1-\sigma A_i}}$	EQ 5.4	Armington function for demand of imports into the domestic economy
$XDD_{i,t} = \frac{X_{i,t}}{\lambda A_i} * \left(\frac{(1-\gamma A_i)}{PDD_{i,t}}\right)^{\sigma A_i} * \left(\left(\left(\gamma A_i^{\sigma A_i}\right) * \left(PM_{i,t}^{(1-\sigma A_i)}\right)\right) + \left((1-\gamma A_i)^{\sigma A_i} * \left(PDD_{i,t}^{(1-sigmaA_i)}\right)\right)\right)^{\frac{\sigma A_i}{1-\sigma A_i}}$	EQ 5.5	Armington function for demand of locally produced goods within the local economy
$P_{i,t} * X_{i,t} = PM_{i,t} * M_{i,t} + PDD_{i,t} * XDD_{i,t}$	EQ 5.6	Zero profit condition for the Armington function
$PM_{i,t} = (1 + tm_i) * ER_t * PWM_{i,0}$	EQ 5.7	Price of imports
$PE_{i,t} = ER_t * PWE_{i,t}$	EQ 5.8	Price of exports
$\sum_i (M_{i,t} * PWM_{i,0}) = \sum_i (PWE_{i,0} * E_{i,t}) + SF_t$	EQ 5.9	Zero profit condition for international trade
Market clearing		
$X_{i,t} = C_{i,t} + I_{i,t} + CG_{i,t} \sum_j (io_{i,j,t} * XD_{j,t})$	EQ 6.1	Market clearing for output
$TSS_{i,t} = \sum_i TS_{i,t}$	EQ 6.2	Market clearing for softwood

$\boldsymbol{THS_{i,t} = \sum_{i} TH_{i,t}}$	EQ 6.3	Market clearing for hardwood
$\boldsymbol{KS_{i,t} = KG_t + \sum_{i} K_{i,t}}$	EQ 6.4	Market clearing for capital
$\boldsymbol{LS_{i,t} = LG_t - UNEMP_t + \sum_{i} L_{i,t}}$	EQ 6.5	Market clearing for labour
Market closures		
$\boldsymbol{\overline{LS_t} = LS_t}$	EQ 7.1	Exogenously fix labour supply
$\boldsymbol{\overline{KS_t} = KS_t}$	EQ 7.2	Exogenously fix capitula supply
$\boldsymbol{\overline{TSS_t} = TSS_t}$	EQ 7.3	Exogenously fix softwood supply
$\boldsymbol{\overline{THS_t} = THS_t}$	EQ 7.4	Exogenously fix hardwood supply
$\boldsymbol{\overline{SG_0} = SG_t}$	EQ 7.5	Exogenously fix government saving
$\boldsymbol{\overline{SF_0} = SF_t}$	EQ 7.6	Exogenously fix government saving
$\boldsymbol{\overline{PL_0} = PL_t}$	EQ 7.7	Fix price of labour (wages) for the numeraire
Dynamic growth pathways		
$\boldsymbol{\overline{LS_t} = LS_{t-1} * (1 + GRL_t)}$	EQ 8.1	Exogenously fixing the labour supply growth path
$\boldsymbol{RRR_t = \frac{S_t * \psi}{PK_t * KS_t}}$	EQ 8.2	Real rate of return
$\boldsymbol{\overline{KS_t} = KS_{t-1} * (1 + RRR_t)}$	EQ 8.3	Exogenously fixing the capital supply growth path
$\boldsymbol{\overline{TSS_t} = TSS_{t-1} * (1 + \mathrm{GRSS_t})}$	EQ 8.4	Exogenously fixing the softwood supply growth path
$\boldsymbol{\overline{THS_t} = THS_{t-1} * (1 + GRHS_t))}$	EQ 8.5	Exogenously fixing the hardwood supply growth path

Chapter 3 Economic impacts of climate change with harvesting interactions: a PICUS-LANDIS II-CGE model analysis in Quebec.

3.1 Abstract

Numerous forestry studies examine the manner in which climate change will affect economically important tree species, and several have also assessed the manner in which harvesting rates influence this relationship. However, these studies seldom quantify the economic impact. This study contributes to the literature by joining a PICUS-LANDIS II model with a CGE model to estimate how climate change interacts with harvesting rates to impact wood supply and the economy. In the case study region of Québec, we estimate that, under the current ecosystem-based harvesting rate, climate change (i.e., RCP 4.5 or 8.5) will reduce the biomass harvested of some softwood species by up to 82% and increase the biomass harvested of some hardwood species by up to 62% in 2150. Doubling the harvesting rate has a significantly positive impact on the supply of both hardwood and softwood supply with a trade-off of a minor reduction (1-5%) in the above ground biomass, an increase in vulnerability of wood supply to climate change, and wood supply shortages in 2070, 2090 and 2140. Halving the harvesting rate, on the other hand, tends to have the opposite effect. Wood-related sectors are the most sensitive to changes in hardwood and softwood supply, with the largest change in value of output occurring in both the softwood (-70% to +37%) and hardwood (-52% to 104%) forestry and logging sectors, depending on the harvest rate and climate change scenario considered, by 2150. The sector-level impacts translate to an annual reduction of up to 0.1% to an annual increase of up to 0.07% in provincial GDP, by 2150.

3.2 Introduction

Québec's forests play a significant role in defining the provincial landscape as 50% or approximately 90 million hectares, of the province is covered in forests. This which accounts for approximately 20% of Canada's forests and 2% of the world's forests (Government of Québec, 2016). The abundance of forests has led Québec to develop one of Canada's largest forestry and logging sectors, producing $868 million worth of goods and services in 2018 (Statistics Canada, 2022a), and employing 8,500 individuals (Statistics Canada, 2021c). Additionally, the forestry and logging sector is responsible for harvesting approximately 28 million m^3 of wood annually with 22 million m^3 (78%) of which is softwood (CCFM, 2020a). This high dependence on the provincial wood supply makes Québec's Forestry and Loggings sector particularly sensitive to potential changes in the structure and productivity of the provincial forest from climate change.

Climate change is projected to have a significant impact oi Québec's forests with individual regions undergoing varying degrees of change (Boulanger et al., 2022; Wang et al., 2023). As Québec's forests cover a substantial area the changes will be heterogeneous with the main agent of change varying between regions. For instance, temperature is expected to increase across the provinces, with inland areas seeing the largest increase, and eastern parts bordering the St Lawrence river experiencing the smallest degree of change (Boisvert-Marsh et al., 2014; Yagouti et al., 2008). Meanwhile, annual precipitation is projected to increase within the province (Vincent et al., 2015). The increase in precipitation will not be enough offset the increase in temperature and as such the likelihood and severity of droughts and forest fires

(Boulanger et al., 2013, 2014; Le Goff et al., 2007; van Bellen et al., 2010) is expected to increase with northwestern Québec experiencing the largest increase in annual area burned, fire occurrences, and mean fire size (Boulanger et al., 2013).

The climate induced alteration of ecosystem processes is expected to impact individual tree species differently spatially. For instance, cold-adapted softwood species, which are currently at their southernmost range limit in southern Québec, may experience a reduction in survivability and productivity in southern Quebec (D'Orangeville et al., 2018; Vaughn et al., 2021). Yet, these reductions could be partially offset by a concurrent the increase in growth rate of cold-adapted tree species in managed forest in northern Québec under climate change (Wang et al., 2023).

Meanwhile, more southerly, warm-adapted hardwood species may experience an limited poleward expansion of their range, as the cold-limited environment becomes warmer (Sittaro et al., 2017). Recent studies suggest that warm-adapted hardwood species, such as red maple, may only experience a minor increase in fitness relative to current fitness levels (Vaughn et al., 2021); yet, that this minor increase in conjunction with the large projected decrease in competitiveness of cold-adapted softwood species and the ability of the species to reproduce vegetatively following increased disturbances will result in a substantial shift in forest composition across the southern portion of the province (Boulanger et al., 2017, 2019; Brecka et al., 2020; Taylor et al., 2017).

As climate change is expected to impact various aspects of the forest landscape through changes in various drivers (e.g., forest productivity, and fire disturbance, etc.)

it is important to examine the cumulative impact such changes will have on wood supply, especially when accounting for interact effect of different harvesting activities. One technique that is growing in application is the use of process-based forest simulation models, as they are able to incorporate both the interacting impacts of climate and management on forest dynamics (Bonan & Doney, 2018; Thom et al., 2017). A recent popular example is the PICUS-LANDIS modeling framework which based on a coupling of two forest models that operate at different ecological scales. PICUS (Lexer & Hönninger, 2001) is an individual tree-based forest stand model that simulates the germination, growth, and death of individual trees within a forest stand (e.g., generally 1-100 ha in size). Trees interact for resources, simulating stand-level forest dynamics. LANDIS-II (Scheller et al., 2007) is coarser level, spatially explicit, raster-based model, that simulates landscape-level forest dynamics by integrating stand-level data provided by PICUS while accounting for wide-scale anthropogenic and nonanthropogenic disturbances (De Jager et al., 2019; Scheller et al., 2011; Schrum et al., 2020).

Recently, Brecka et al. (2020) used PICUS-LANDIS to examine how various climate forcing scenarios and harvesting rates interacted to affect forests wood supply in Canada. The study showed that climate change will negatively impact both the biomass harvested, and area harvested in the Boreal Shield East Ecozone[14], with cold-adapted softwood species being the most sensitive to climate change. Under severe

[14] The Boreal Shield East Ecozone coves the Boreal Forest, as such it is found in Western Quebec and stretches northeast to Newfoundland and Labrador. The Boreal Shield East Ecozone is bound by the Boreal Shield West Ecozone to the West, the Mixedwood Plains to the south, the Atlantic Maritimes to the east and the Taiga shield to the north.

climate change and high harvesting activities, the authors predicted total biomass harvested in the Boreal Shield East Ecozone may decrease by approximately 40% by 2200. Furthermore, reducing the harvesting rate reduces the intensity of climate change negatively impacting the forest and as such reduces the decrease in biomass harvested. Specifically, the low harvesting intensity scenario experiences smaller reduction in wood supply by later half of the 21st century when compared to a high harvesting scenario under severe climate change. They concluded that Canada's forestry sector should consider reducing harvesting rates in order to ensure a steady, sustainable wood supply in the face of changing climate.

Forest modeling studies, including the various PICUS-LANDIS based investigations, provides important insight on the biophysical impacts of climate and management activities. However, these studies do not conducted a formal economic analysis to examine economic impacts. This is especially important when examining the forestry sector, as although a decrease in harvesting activities may improve the long-term resilience of the forest and ensure a sustainable wood supply under climate change, such actions will almost certainly result in short-term economic losses.

Computable general equilibrium (CGE) models are an economic tool that uses neo-classical economic theory to simulate how the economy will react to a market shock (e.g., change in prices, availability of factors of production, or output). Recently, CGE models have been used to analyze the economic impact caused by changes in regional wood supplies (Corbett et al., 2016; Lantz et al., 2022; Liu et al., 2019; Ochuodho et al., 2012).

Ochuodho & Lantz, (2014) and Boccanfuso et al. (2018) both employed a single region CGE model to examine the economic impact of climate change in provincial wood supply. The studies found that such changes in the province of Québec could result in impacts ranging from a 0.061% to 0.098% increase in cumulative GDP between 2006-2051 (Ochuodho & Lantz, 2014), to a 0.12% reduction in GDP by 2050 (Boccanfuso et al., 2018). The discrepancy between studies is largely due to different assumptions each study made about how climate change and climate mitigation strategies will impact wood supply. Specifically, both studies relied on peer-reviewed literature (e.g., Flannigan et al., 2005; Lemprière et al., 2008; Yamasaki et al., 2012) and expert opinion to determine the impact on wood supply, which resulted in significantly different projections

A second major shortcoming in both Ochuodho & Lantz, (2014) and Boccanfuso et al. (2018) is they both consider an aggregated estimate of wood supply change instead of differentiating between hardwood vs. softwood supply changes. In doing so they are unable to account for climate-induced changes in the structure or composition of the forest. The distinction between hardwood and softwood species is important as not only is climate change expected to impact cold-adapted species differently than warm-adapted species (Boulanger et al., 2017, 2018; Brecka et al., 2018; Vaughn et al., 2021), but also each species contains a different economic value (Québec's Bureau de mise en Marché des bois, 2017). Recent forestry-related CGE studies have addressed this oversimplification by disaggregating wood supply into hardwood vs. softwood supply and joining the CGE model with either a forest management planning model

(e.g., Woodstock[15]) (Lantz et al., 2022) or a process-based forest simulation modeling framework (e.g., PICUS-LANDIS) (McMonagle, et al. 2022). In doing so, these studies use forest models to more accurately simulate the effects of climate change on the biophysical environment and derived wood supply.

Another limitation of these studies is they do not consider how a change in harvesting rates effect the intensity of climate change altering forest structure. As previously mentioned, several forest modeling studies have found strong interactive effects between climate change and harvesting rates (Brecka et al., 2020; Gauthier et al., 2015; Navarro et al., 2018; Taylor et al., 2020; Tremblay et al., 2018). It would be of interest to assess the extent to which these interactions influence the economic impact estimates, while also examining the economic and ecological trade-offs

This study aims to use the PICUS-LANDIS-CGE modeling framework developed by McMonagle et al. (2022) to examine how climate change and harvesting rates interact to impact the long-term ecological and economic viability of the forestry sector and the economy in the case-study region of Québec, Canada. Based on previous studies (e.g., Boulanger et al., 2019; Brecka et al., 2020), we hypothesize that reducing the harvesting rates will reduce the impact climate change has on wood supply (and vice-versa). It will be of interest to see the manner in which these interactions affect the overall provincial wood supply, the forest sector, and the economy.

[15] Woodstock is a forest management planning model produced and sold by Remsoft (www.remsoft.com/woodstock-optimization-studio/), that simulates a forest under a user defined scenarios using a Monte-Carlo analysis. In addition to being used by various governments to manage crownland, it has been used in academia to study how climate change and climate mitigation strategies will impact various components of a forest (Dhital et al., 2015; Dymond et al., 2020; Lundholm et al., 2019, 2020)

The remainder of this paper is divided into the following sections. Section 2 describes the methodology, including the case study region along with the calibration of the PICUS-LANDIS II-CGE framework and the scenarios we consider for this case study. This is followed by section 3, which presents results associated with the ecological and economic impacts of harvesting rates interacting with climate change. Section 4 provides a discussion of the significance of the findings, as well as addresses the current limitations of the PICUS-LANDIS II-CGE framework. Lastly, section 5 contains the conclusion of the study and highlights the importance of future research examining climate change through a multidisciplinary lens.

3.3 Methods and data

3.3.1 Study area

The commercial forest in Québec covers approximately 54.3 million ha of the province (Boulanger & Puigdevall, 2021), with the majority (92%) of the forest located on public land (Crownland), and the remainder split among 130,000 different woodlot owners (Government of Québec, 2016). The commercial forest covers both the Boreal Forest Region and the Great Lakes-St Lawrence Region (Rowe, 1972). The Boreal Forest Region is the largest of the two regions and is located across central and northern Québec. The region is characterized by cold-adapted tree species, with balsam fir (*Abies balsamea*), tamarack (*Larix laricina*), red pine (*Pinus resionosa*), white birch (*Betula papyrifera*), white spruce (*Picea glauca*), black spruce (*Picea mariana*), and jack pine (*Pinus banksiana*) being defining species.

The Great Lakes-St Lawrence Forest Region is found in the southern part of the province, along the St Lawrence River. The region has a more temperate climate compared to the Boreal Forest Region. This warm temperature favours warm-adapted tree species, such as red maple (*Acer rubrum*) sugar maple (*Acer saccharum*), and northern red oak (*Quercus rubra,* Rowe, 1972). The transition zone between the two regions consists of a mixture of warm-adapted species from the Great lakes-St Lawrence region and cold-adapted species from the boreal forest region (Rowe, 1972).

Due to the size of the forest regions and the diversity of the ecosystems found in each, Quebec's forests can be divided into four sub-regions (Figure 3.1): boreal forest east, boreal forest west, mixed forest, and the northern hardwood forests. These regions are based on bioclimatic subdomains (Robitaille & Saucier, 1998). As the name suggests, the boreal forest east and boreal forest west are both found within the Boreal Forest Region. Meanwhile, the northern hardwood forest is located in the Great lakes-St Lawrence Forest Region. Lastly, the mixed forest represents the transition zone between the Boreal Forest Region, and the Great-Lakes-St Lawrence region.

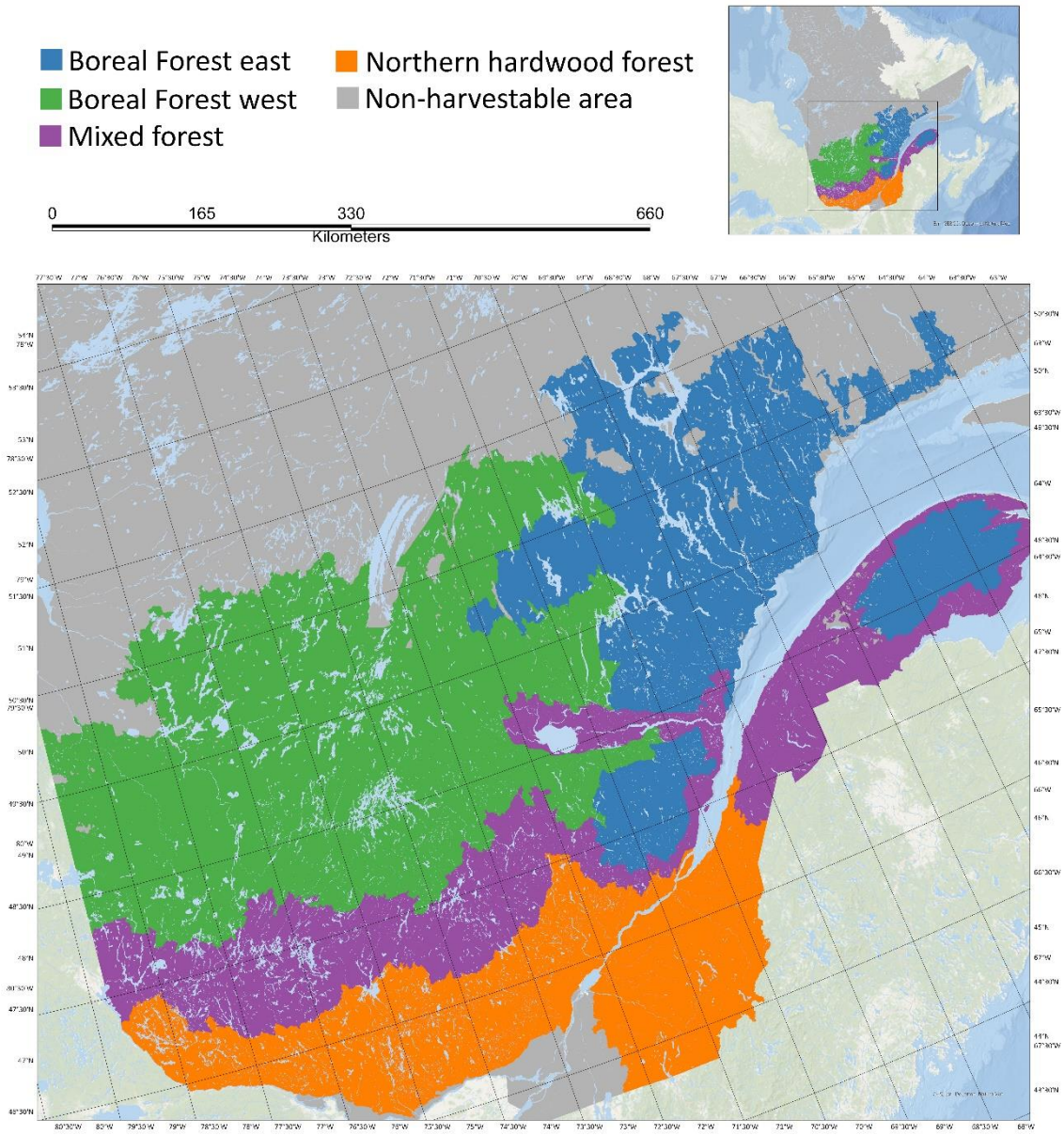

Figure 3.1 Location of the four forests area (Boreal Forest east, Boreal Forest west, mixed forests, and northern hardwood forest) in Quebec

3.3.2 PICUS-LANDIS framework

We use PICUS-LANDIS to simulate forest landscape dynamics and ecosystem processes under various climate and harvesting scenarios. PICUS-LANDIS is made up of two separate models: PICUS and LANDIS-II. The coupling of these models is well established with the framework being used in previous studies (e.g. Boulanger et al., 2017, 2018; Brecka et al., 2020; St-Laurent et al., 2022; Tremblay et al., 2018).

PICUS (V1.5; Lexer & Hönninger, 2001) is a forest gap model that simulates the germination, growth, and death of individual trees within a 10 m x 10 m forest patch under different environmental and soil characteristics.

PICUS is calibrated for eastern Canada using provincial sample plots (Taylor et al. 2017). We run PICUS[16] simulation for the study area by using specific climate (D. W. McKenney et al., 2011) and soil (Mansuy et al., 2014) parameters. PICUS is run for four separate time periods (2000-2010, 2011-2040, 2041-2070 and 2071-2100) under three climate change scenarios; no climate change, RCP 4.5, and RCP 8.5 (climate scenarios are explained further in section *2.6 Scenarios and Climate data)* as well as for each tree species and landtype separately. Landtypes are regions in which climate and soil conditions are homogeneous.

LANDIS-II is a spatially explicit raster-based model that simulates forest dynamics across a landscape. We initialize LANDIS-II to current Québec conditions and ensure an accurate representation of each the current forest conditions in each raster

[16] A detailed explanation of PICUS and tree specific parameters can be found in Taylor et al. (2017).

cell by using Québec's ecoforestry maps in conjunction with data from the provincial forestry inventory plots (FIP)[17]. Details regarding PICUS and LANDIS-II simulations for the present study can be found in Boulanger and Pascual (2021).

In this study, anthropogenic disturbances take the form of harvesting, which we simulate using the Biomass Harvest extension (V4.0; Gustafson et al., 2000)[18]. The extension simulates harvesting using forest management units (FMU), with each FMU being able to contain specific harvesting prescriptions. In the study, we assign prescriptions according to the ecosystem-based forest management as it currently prevails in the province. These include clear-cuts and various partial harvesting simulated at various rates depending on regions and potential vegetation. In our simulations each species is harvested according to its abundance in the stand, with no specific weight given to a particular species. Details about harvesting strategies are available in Boulanger et al. (2019). The harvesting rate is explained further in *2.5 scenarios and climate data*.

Non-anthropogenic disturbances included forest fires and spruce budworm (SBW, *Choristoneura fumiferana*,[Clem]) outbreaks. These two disturbances make up the majority of the natural disturbances that occur within Québec (Boucher et al., 2017). LANDIS-II simulates forest fires using the Base Fire extension (v*), which treats fire as a stochastic event that is influenced by cell-level parameters including likelihood

[17] LANDIS-II has been calibrated extensively for the province of Québec, a detailed description of this process can be found in Boulanger and Pascual (2021).
[18] A detailed explanation of the calibration of the non-anthropogenic disturbances can be found in McMonagle et al. (2022).

of fire ignition and spread. Current and future fire regime parameters are derived from models developed by Boulanger et al. (2014) and further updated for Representative Concentration Pathways (RCP) scenarios and are summarized for each of the homogeneous fire region of Boulanger et al. (2014) overlapping the study area. Annual area burned projected from those models were further refined by considering potential negative-feedback of fire with the forest age structure as in Boulanger et al. (2017). We use the Biological Disturbance Agent (BDA) extension (V4;) Sturtevant et al., 2004) to simulate SBW outbreaks. The BDA models host tree (balsam fir, white, red and black spruces) mortality during an SBW outbreak according to stand and landscape scale susceptibility and vulnerability as defined by Boulanger et al. (2016) for the mixedwood forest.

3.3.3 Computable General Equilibrium (CGE) model

The study employs a single-region recursive dynamic computable general equilibrium (CGE) model to analyze the economic impact of a change in quantity and composition of wood supply. CGE models are based on neoclassical economic theory and were first described by Dervis et al., (1982) to address limitations of input-output analysis. CGE models use a system of equations[19] to simulate how an economy will react to a market shock, with shocks taking several forms including changes in prices, taxes, and factors of production (e.g., labour, capital, energy, wood).

[19] A detailed list of equations and variables can be found in the appendix.

The CGE model in this study is similar in structure to the ones that were used by Lantz et al. (2022) and McMonagle et al. (2022). As such, a more detailed explanation of the model can be found in these studies. The model treats Québec as a small open economy, that is made up of 27 sectors (Table 3.1), eight of which we classify as forestry or wood-related sectors (Table 3.2). These wood-related sectors all have a higher demand for hardwood and softwood outputs (Table 3.3) compared to non-wood related sectors. As such, they are especially sensitive to a change in either the quantity or composition of wood supply. In addition to the 28 sectors, there are also four agents: the household, the government, the bank, and the foreign market (which is referred to as the Rest of World (RoW) from this point forward). As a small open economy, Québec has access to the RoW through imports and exports, however, it does not influence world prices or the international supply and demand of commodities. Furthermore, at the end of each period, all markets are fully cleared.

Table 3.1 Production sectors included in Québec's CGE model

sec1	Crop & Animal Production (CROP)	sec15	Other Manufacturing (OTH-MANUF)
sec2	Softwood Forestry and Logging (S-FOR)	sec16	Wholesale Trade (TRADES)
sec3	Hardwood Forestry and Logging (H-FOR)	sec17	Retail Trade (RET)
sec4	Fishing, Hunting & Trapping (FISH)	sec18	Transportation (TRANSP)
sec5	Support Activities for Agriculture and Forestry (SUPP)	Sec19	Information (INFO)
sec6	Mining Quarrying, Oil & Gas Extraction (OILGAS)	Sec20	Finance (FIN)
sec7	Utilities (UTL)	sec21	Professional (PROF)
sec8	Construction (CONST)	sec22	Administration (ADMIN)
sec9	Sawmill & Wood Preservation (SAW-MANUF)	sec23	Education (EDUC)
sec10	Veneer Plywood Manufacturing (VEN-MANUF)	sec24	Health Care (HEALTH)
sec11	Other Wood Product Manufacturing (OW-MANUF)	sec25	Entertainment (ENT)
sec12	Pulp, Paper & Carboard Mills (PUP-MANUF)	sec26	Accommodation & Food Services (ACC)
sec13	Converted Paper Product Manufacturing (CP-MANUF)	sec27	Other Goods & Services (OG&S)
sec14	Printing & Related Activities (PR-MANUF)		

Table 3.2 Wood-related production sectors

sec2	Softwood Forestry and Logging (S-FOR)
sec3	Hardwood Forestry and Logging (H-FOR)
sec9	Sawmill & Wood Preservation (SAW-MANUF)
sec10	Veneer Plywood Manufacturing (VEN-MANUF)
sec11	Other Wood Product Manufacturing (OW-MANUF)
sec12	Pulp, Paper and Carboard Mills (PUP-MANUF)
sec13	Converted Paper Product Manufacturing (CP-MANUF)
sec14	Printing & Related Activities (PR-MANUF)

Table 3.3 Initial demand for softwood and hardwood intermediate goods by major manufacturing sectors in Québec ($ millions)

	SAW-MANUF	VEN-MANUF	OW-MANUF	PUP-MANUF	CP-MANUF	PR-MANUF	Rest of the economy
S-FOR	13670	1713	936	1963	4	2	878
H-FOR	1843	231	126	412	1	0	176

We treat production sectors within Québec as price takers, which assumes they are unable to control the price of commodities. Sectors are modeled as a representative firm, and each firm produces a sector-specific commodity using a combination of intermediate inputs and four factors of production (capital, labour, hardwood supply, and softwood supply). Similarly to Ochuodho & Lantz, (2014), we assume all four factors of production are owned by the household and as such, they receive payments in the form of wages, rent, and hardwood/softwood stumpage. Capital and labour are mobile across sectors while hardwood and softwood supply are exclusively demanded by their corresponding hardwood and softwood forestry and logging sector. The household also receives income from two government transfers: a general transfer, and an unemployment transfer.

The production block contains equations specific to the production of domestically produced commodities. There are three levels (nests) within the production block, each of which allows firms to optimize their output based on the current prices of intermediate goods and factors of production. The first nest is a fixed share Leontief production function in which firms select between intermediate goods and a hardwood-softwood-capital-labour bundle[20]. The second nest is a constant elasticity of substitution (CES) function that combines a bundling technique (Timilsina et al., 2012) with a multifactor production function (Lofgren et al., 2002). This allows firms to select their optimal amount of hardwood, softwood, and capital-labour

[20] The fixed share Leontief production function assumes firms have had time to determine their optimal mix of intermediate inputs. In doing so the substitution of intimidate inputs is based on the demand of intermediate inputs seen within the SAM.

bundle[21]. The final nest is a standard two-factor CES function in which firms choose between capital and labour. Firms maximize their output while being restricted by the zero-profit condition, the supply of intermediate goods, and the availability of factors of production.

Firms sell their output as either intermediate goods or final consumption goods. Intermediate goods are bought by other firms and are used within the production block. Meanwhile, final consumption goods are sold to either the domestic market or the RoW, with the domestic market being made up of the household, the government, and the bank[22].

There are several variables within the CGE model which we fix in order to act as market closures. Hence, these variables are not solved within the CGE framework but are rather are exogenous. Market closures include foreign savings, government savings, general transfers, and the endowment of capital, labour, hardwood supply, and softwood supply. Lastly, the price of labour is set to one to act as the model's numeraire.

3.3.4 Calibrating the CGE model

We code and solve the CGE model in General Algebraic Modeling Systems (GAMS) version 31.1.1 (GAMS Development Corporation, 2020) using the conop3 solver. We use the loop function to make the model recursive dynamic with growth

[21] This approach allows for regular substitution between capital and labour, while also limiting the suitability of hardwood and softwood for the forestry sectors.
[22] A detailed explanation of the trade, household, government, and investment block of the CGE model can be found in either Lantz et al. (2022) or McMonagle et al. (2022).

rates being applied to capital, labour, hardwood supply, and softwood supply. The growth rate of labour is parameterized using the projected labour force growth rate of Québec (Martel, 2019). This equates to a short-term (2015-2030) growth rate of -1.2% per five years, and a long-term (2030 – 2150) growth rate of 4.3% every ten years. The steady state growth rate which we use to determine capital accumulation was also set to 4.3% every ten years, which simulates the historic change in unemployment within Québec (Statistics Canada, 2022c). The growth rates for hardwood and softwood supply is explained in section 2.4.

To calibrate the CGE model to Québec we use a Social Accounting Matrix (SAM) based on the year 2015. We construct Québec's SAM using Statistics Canada's provincial symmetric input-out table (Statistics Canada, 2015), household accounts (Statistics Canada, 2015a), and stumpage revenues (CCFM, 2020b). We aggregate the provincial symmetric input-out (I-O) table "detailed level" down to 26 sectors from the original 230. These 26 sectors become the base of the SAM as the symmetric input-out provides information regarding the flow of goods and services between sectors and agents in dollar value. This allows us to determine both the intermediate and final demand for output. Additionally, the I-O table contains information regarding the transfer of wages and rent between sectors and the household. Tax rates on factors of production and consumption are collected from the World Banks's Better Business Project (World Bank, 2020). We determine sector-specific tariff rates using GTAP's TASTE program (Horridge & Laborde, 2008). The rates are held constant throughout the simulations.

As previously noted, the symmetric input-output table does not contain information regarding stumpage payments. As such we follow past studies (i.e., Lantz et al., 2022, McMonagle et al, 2022, Ochuodho & Lantz, 2014) to determine the crownland stumpage value. We use the quantity of wood supply harvested by grade and species along with the stumpage rates to determine the proportion of revenue generated by grade and species. This is scaled up to the entire province by including private land stumpage which follows the same process just described for Crownland forests. When Crownland and Private land stumpage revenues are combined, they create the total value stumpage that is paid by the Forestry and Logging sector. We assume that this amount is nestled within the Forestry and Logging sector's capital.

To separate the Forestry and Logging sector into Hardwood vs Softwood Forestry and Logging subsectors, we follow the methodology established in Lantz et al. (2022) and McMonagle et al. (2022) by using the quantity of wood harvested by grade and species, local stumpage prices by grade and species, and Québec's 2015 supply and use table (Statistics Canada, 2020)[23].

To calibrate the household to Québec we use the Statistics Canada 2015 household account (Statistics Canada, 2020b), which contains information regarding transfers, and the household's marginal propensity to save. We determine the current unemployment within the economy, using an initial rate based on Québec's 2015 unemployment level (Statistics Canada, 2015).

[23] Lantz et al. (2022), and McMonagle et al. (2022) both describe the methodology used to disaggregate S-FOR and H-FOR from the Forestry & Logging sector.

The CGE model also requires various elasticity parameters, which represent sectors' and agents' preferences and willingness to switch between goods and/or factors of production as the market changes. We collect the elasticities from peer-reviewed literature as follows: (i) elasticities of substitution between factors of production are taken from Okagawa and Ban (2008); (ii) elasticities of household consumption are taken from Huff et al. (2012); (iii) elasticities for the Armington functions are taken from Huff et al. (2012); and (iv) elasticities for the CET functions are taken from Arndt et al. (2001). The elasticities of substitution between hardwood, softwood, and the capital-labour bundle for the hardwood and softwood forestry and logging sectors are set to relatively low values, following other forestry-related CGE studies[24].

2.3.5 Scenarios and climate data

We ran the PICUS-LANDIS analysis under nine distinct scenarios (Table 3.3). The scenarios have unique combinations of harvesting rates and climate change. Specifically, we defined three harvesting rate scenarios, including: (i) a baseline harvesting rate which is calibrated using approximate theoretical annual allowable cut (AAC) rates under ecosystem-based forest management as it is currently prescribed in

[24] There is a lack of peer reviewed studies that have estimated these elasticities. Hence, we follow past forestry related CGE studies (Corbett et al., 2016) and assume that wood supply is a key factor of production for the Forestry & Logging sectors and as such there is a low rate of substitution between hardwood and softwood supply and other factors of production.

the province[25]; (ii) a harvesting rate equal to one half of the baseline rate (Half AAC); and (iii) a harvesting rate equal to double the baseline rate (Double AAC)[26]. We also considered three climate change scenarios, including: (i) a baseline of no climate change (No CC); (ii) climate change associated with the IPCC's RCP (van Vuuren et al., 2011) 4.5 (RCP 4.5); and (iii) climate change associated with the IPCC's RCP 8.5 (RCP 8.5).[27] The RCP number represents the peak radiative forcing (W/m^2) by 2100.

[25] The AAC rates are based of area harvested and not volume harvested.

[26] We recognize that multiplying or dividing the current AAC by a factor of two is unlikely, however the point of this study is to examine how a change in harvesting rates interact with climate change to impact wood supply and the economy, and as such we decided to use these values as they provide the clearest perspective.

[27] RCP 2.5 is emitted from this case study due to the similarity in economic impacts between RCP 2.5 and RCP 4.5.

Table 3.4 Description of scenarios

Scenario	Descriptor	Harvest rate	Climate change
1	Baseline	Annual allowable cut[a]	No climate change
2	AAC & RCP 4.5	Annual allowable cut[a]	RCP 4.5
3	AAC & RCP 8.5	Annual allowable cut[a]	RCP 8.5
4	Half AAC & No CC	Half annual allowable cut	No climate change
5	Half AAC & RCP 4.5	Half annual allowable cut	RCP 4.5
6	Half AAC & RCP 8.5	Half annual allowable cut	RCP 8.5
7	Double AAC & No CC	Double annual allowable cut	No climate change
8	Double AAC & RCP 4.5	Double annual allowable cut	RCP 4.5
9	Double AAC & RCP 8.5	Double annual allowable cut	RCP 8.5

[a] Based on the historical annual allowable cut in the province, at approximately 1% of the operable growing stock.

To input monthly climate characteristics to PICUS-LANDIS we used climate data from McKenney et al. (2013) to interpolate climate station records across Québec. The Baseline climate scenario is based on the observed climate between 1981-2010, with the RCP scenarios determined using the Canadian Earth System Model v.2 (CanESM2), with data from the World Climate Research Program (WCRP) Climate Model Intercomparison Project Phase 5 (CMIMP5)[28] and further downscaled at a 10-km resolution using ANUSPLIN (McKenney et al. 2013).

For each of the climate change and harvesting scenarios considered, we use the PICUS-LANDIS framework to assess the change in mean above-ground biomass, as well as biomass harvested (t/ha) of individual tree species trends over the 2015-2150 period. The economic impact of each scenario was estimated by incorporating the biomass harvest into the CGE model[29]. In doing so we assume that a percent change in biomass harvested of hardwood and softwood between times periods is equivalent to a percent change in supply of hardwood and softwood. We use the CGE model to present sector-level output and prices, along with a series of macro-economic variables in baseline and each scenario. These variables include: gross domestic product (GDP); household income (Y); equivalent variation (EV)[30]; household consumption (C); government consumption (CG); investment (INV); exports (EXP); imports (IMP);

[28] A detailed explanation of the process used to determine climate characteristics can be found in Boulanger et al. 2017.
[29] McMonagle et al. (2022) describes the joining between PICUS-LANDIS and the CGE model.
[30] Equivalent variation is a measure of social welfare. It represents a change in income, at current prices, that would have the same effect on consumer utility as would a change in prices, with income unchanged. It is measured as the difference between: (i) the supernumerary income that would exist under the proposed change divided by a price index that reflects the change in prices under the proposed change; and (ii) the supernumerary income that exists under baseline conditions.

domestic output (XD); domestic output delivered domestically (XDD); labour (L); and capital (K). Cumulative present values are included using a 2% real discount rate reflecting the rate of return of long-term government bonds in Canada in 2015 (Statistics Canada, 2022b).

3.4 Results

3.4.1 Ecological results

3.4.1.1 Impact on the forest landscape

Climate change (RCP 4.5 and RCP 8.5) is shown to have a negative impact on the mean above-ground biomass in all four forest areas; boreal forest east (Figure 3.2), boreal forest west (Figure 3.3), mixedwood forest (Figure 3.4), and the northern hardwood forest (Figure 3.5). Cold-adapted softwood species were the most susceptible to being negatively impacted by climate change, with balsam fir and black spruces experiencing a noticeable reduction in abundance in all forest areas. Meanwhile, several warm-adapted hardwood species experience an increase in mean above-ground biomass under both RCP 4.5 and RCP 8.5, with red maple experiencing the most significant increase in abundance in the mixedwood forest under RCP 4.5. The impact of climate change on mean above-ground biomass is most notable after 2070. Cold-adapted softwood species are disproportionally negatively affected under Double AAC & RCP 8.5, with balsam fir, black spruce and red spruces experiencing the largest decrease compared to other species.

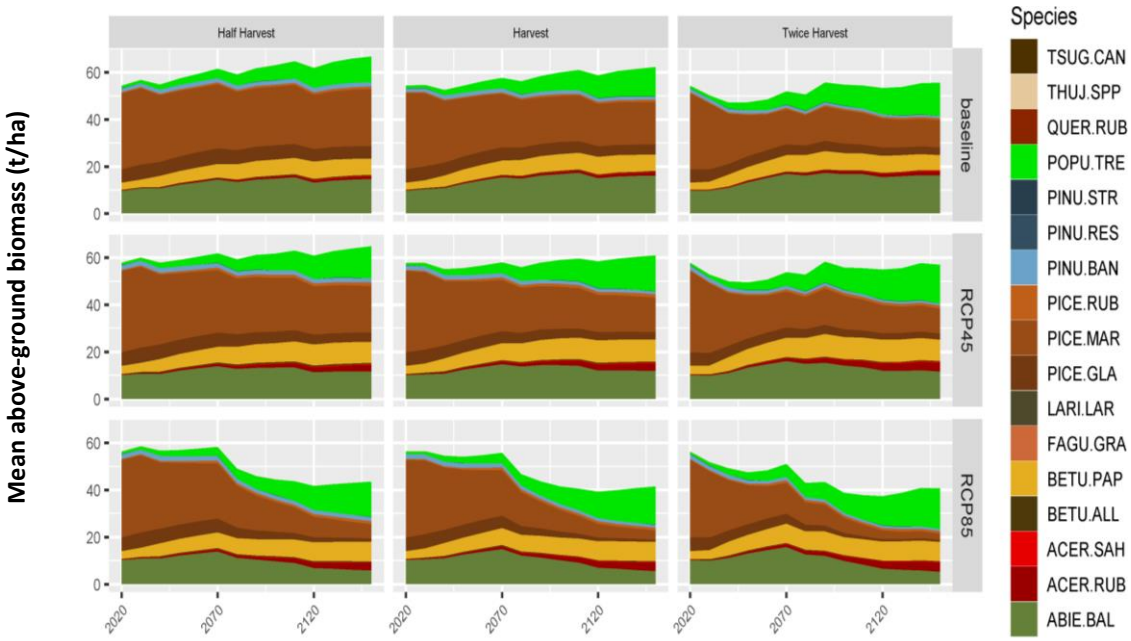

Figure 3.2 Evolution of landscape composition in mean above-ground biomass in Québec's boreal forest east (t/ha))

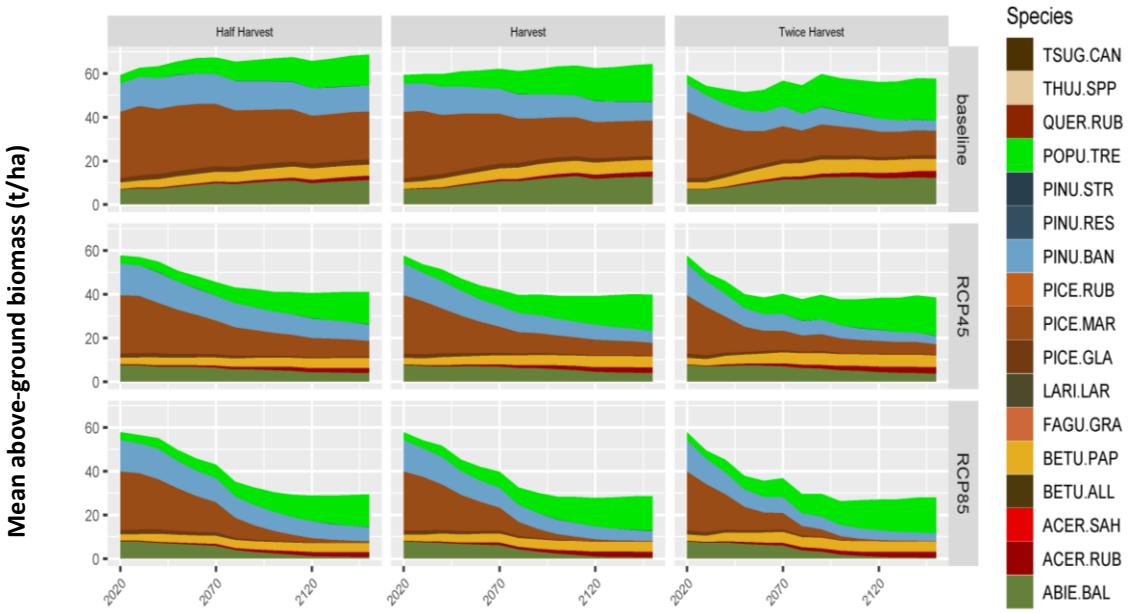

Figure 3.3 Evolution of landscape composition in mean above-ground biomass in Québec's boreal forest west (t/ha)

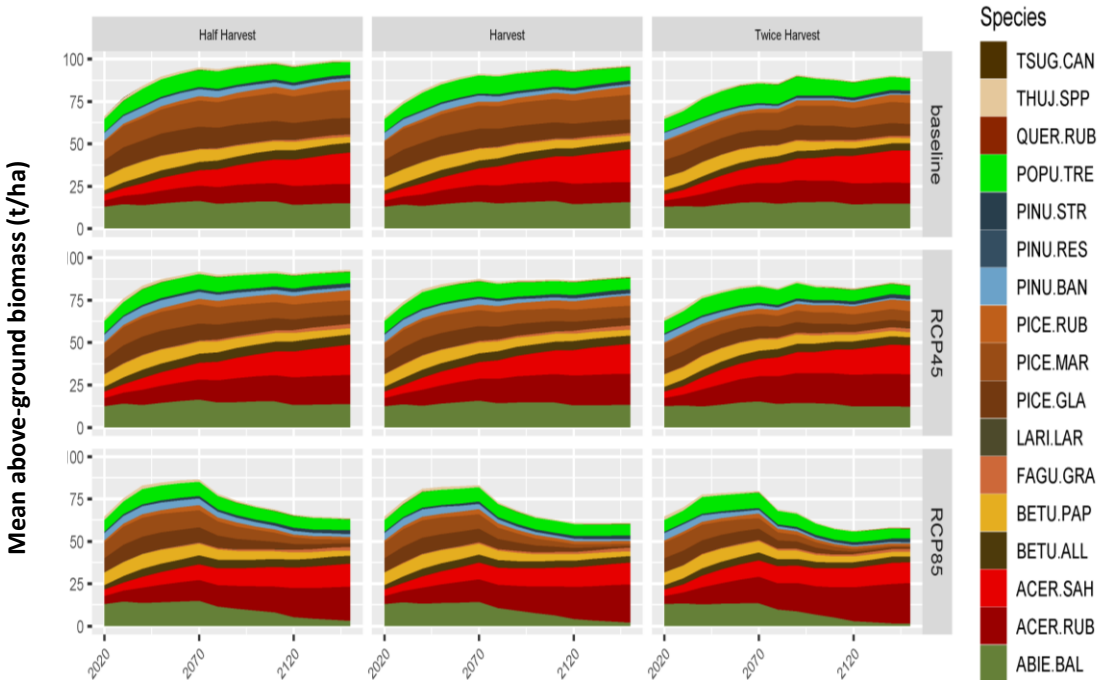

Figure 3.4 Evolution of landscape composition in mean above-ground biomass in Québec' mixedwood forest (t/ha)

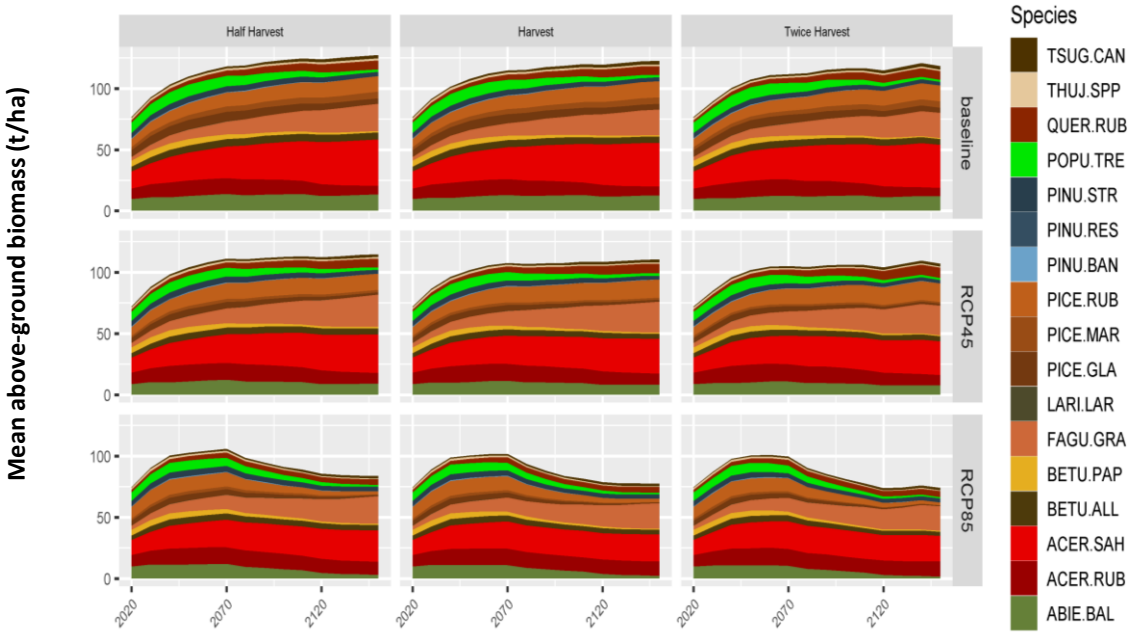

Figure 3.5 Evolution of landscape composition in mean above-ground biomass in Québec's northern hardwood forest (t/ha)

When the AAC is halved and climate change is not accounted for there is an initial increase in above-ground biomass within all forest areas (Figure 3.2-3.5) that is present until 2150. This increase in above-ground biomass is most notable in the Boreal Forest east (Figure 3.2) and the Boreal Forest west (Figure 3.3) as both forest areas experiences a roughly 5% increase in above-ground biomass in the year 2150 compared to the baseline. Doubling the AAC has a negative impact on the mean above-ground biomass within the forest area. For instances, when the AAC is doubled, and climate change does not occur there is roughly a 5% decrease in mean above ground biomass in the Boreal Forest west and the mixed wood forests (Figure 3.4) at 2150 compared to the baseline.

There is an interactive effect between climate change and harvesting rates. Specifically, reducing the AAC lessens the extent to which climate change negatively impacts biomass levels. Furthermore, doubling the AAC in conjunction with RCP 8.5 results in the largest decrease in above-ground biomass across all scenarios. This interaction is most noticeable in the Boreal Forest east and the mixed wood forest. Although there is an interactive effect between climate change and the AAC, under severe climate change the main driver of change within the forest is climate change.

3.4.1.2 Impact on species-level biomass harvested:

Climate change and harvesting intensity have a wide range of impacts on the biomass harvested of individual softwood and hardwood species (Table 3.5). Under the

baseline AAC, cold-adapted softwood species such as balsam fir, tamarack, black spruce, and white spruce are the most negatively impacted tree species in terms of biomass harvested due to a change in climate.

Table 3.5 Biomass harvested of individual tree species in Québec in 2150 (% difference from Baseline)

		Scenarios							
		AAC & RCP 4.5	AAC & RCP 8.5	Half AAC & No CC	Half AAC & RCP 4.5	Half AAC & RCP 8.5	Double AAC & No CC	Double AAC & RCP 4.5	Double AAC & RCP 8.5
Softwood species	Balsam fir	-26.27%	-67.56%	-54.63%	-59.56%	-78.69%	74.64%	13.99%	-64.48%
	Tamarack	-45.39%	-69.03%	-34.23%	-54.36%	-65.41%	-52.52%	-68.03%	-89.17%
	White spruce	-40.65%	-74.64%	-39.98%	-61.43%	-78.56%	38.32%	-22.39%	-76.89%
	Black spruce	-36.91%	-81.74%	-39.46%	-55.98%	-81.89%	23.72%	-23.99%	-85.62%
	Red spruce	25.02%	-54.98%	-48.60%	-38.40%	-76.76%	84.28%	128.65%	-38.05%
	Jack pine	-6.37%	-19.57%	-60.64%	-35.55%	-32.11%	31.09%	-2.81%	-25.77%
	Red pine	19.44%	58.20%	-49.51%	-40.52%	-20.00%	44.43%	60.33%	158.63%
	White pine	13.74%	5.88%	-44.01%	-36.97%	-40.19%	75.03%	91.79%	64.85%
	Cedar	-10.60%	-35.94%	-23.19%	-28.00%	-48.19%	46.99%	30.88%	-9.91%
	Eastern hemlock	-17.28%	-24.51%	-42.25%	-50.84%	-55.30%	73.57%	40.24%	30.07%
Hardwood species	Red maple	44.14%	61.67%	-58.86%	-37.90%	-31.80%	112.44%	180.16%	183.58%
	Sugar maple	-13.30%	-30.49%	-47.28%	-52.57%	-60.74%	99.49%	66.68%	23.61%
	Yellow birch	2.21%	-18.59%	-37.91%	-36.73%	-45.53%	68.64%	65.03%	22.01%
	White birch	11.92%	0.98%	-60.25%	-46.77%	-45.79%	91.06%	88.69%	40.83%
	American beech	26.72%	9.27%	-43.31%	-27.30%	-35.12%	79.46%	123.90%	89.37%
	Poplar	-3.20%	-7.57%	-71.57%	-59.53%	-56.20%	155.79%	80.36%	40.56%
	Northern red oak	16.80%	-32.34%	-50.33%	-49.56%	-70.54%	92.31%	137.27%	24.95%

Hardwood species biomass harvested are also impacted by climate change, with multiple species (e.g., red maple, yellow birch, white birch, American beech, and northern red oak) experiencing an increase in biomass harvested under typical harvesting rates and moderate climate change (RCP 4.5, Table 3.5). A few hardwood species (e.g., sugar maple, and poplar (*Populus balsamifera*) are expected to exhibit a decrease in harvest volume in the range of 7-30%.

When the AAC is halved and there is no climate change effect, it has the obvious impact of reducing the volume harvested of all softwood and hardwood species, compared to the baseline (Table 5). The decreases range between 23-60% and reflect the reduction in the amount that is allowed to be harvested. When climate change effects are also considered (i.e., under Half AAC & RCP 4.5 and Half AAC & RCP 8.5), the negative impact of climate change on susceptible softwood species leads to a larger reduction in harvesting than under Half AAC & No CC. On the other hand, the positive impacts that climate change has on biomass harvested for many warm-adapted hardwood species (e.g., red maple, white birch, American beech, and poplar) tend to reduce the negative impacts of halving the AAC.

When the AAC is doubled and climate change does not occur (i.e., Double AAC & No CC), it has the obvious impact of increasing the biomass harvested of both hardwood and softwood species (except tamarack) compared to the baseline. When climate change effects are also considered (i.e., Double AAC & RCP 4.5 and Double AAC & RCP 8.5), the negative impacts of climate change on biomass harvested for the most climate-vulnerable softwood species tend to reduce the positive impact of increasing

harvesting rates. On the other hand, the positive impact that climate change has on biomass harvested for many hardwoods tends to further enhance the positive impacts of the increased harvesting rate.

When comparing the climate change impacts on individual tree species across the different harvesting rates, it becomes apparent that there are important interaction effects. Specifically, as the harvesting rate intensifies, climate change tends to have a more important impact on the biomass harvested. For example, red maple, which is positively impacted by climate change, had harvest volume increase 62% under RCP 8.5 by year 2150 compared to the baseline scenario. Under the Half AAC scenarios, the impact on the volume harvested, relative to the AAC & No CC scenario, ranges from -57% under No CC to -32% under RCP8.5. Thus, climate change positively impacts red maple by a range of 27% at 2150 in this scenario. Finally, under the Double AAC scenarios, the volume harvested increases by 112% under No CC and by 184% under RCP8.5 compared to the baseline. Thus, when doubling AAC, the climate impact produces an even larger range as the differences in biomass harvested between climate scenario is 71%. This result is also true for negatively impacted species such as balsam fir, which experiences a reduced difference in biomass harvested between climate scenarios as the ACC is halved. As such, we find that the more intensively we harvest the forest, the more sensitive the biomass harvested will be to climate change.

3.4.1.3 Impact on aggregated softwood and hardwood supply:

The change in biomass harvested of individual species is seen further in aggregated supply of softwood (Figure 3.6) and hardwood (Figure 3.7). Under the

baseline AAC, softwood species are negatively impacted by climate change, as such there is a 26% and 67% reduction in the aggerated supply of softwood under ACC & RCP 4.5 and ACC & RCP 8.5, respectively, when compared to ACC & No CC. Meanwhile, hardwood supply experiences a minor 6% increase at 2150 under RCP 4.5, relative to the baseline. As climate change becomes more severe (RCP 8.5), the negative impact it has on the supply of hardwood increases, as at year 2150 there is a 3% reduction in hardwood supply when compared to the baseline.

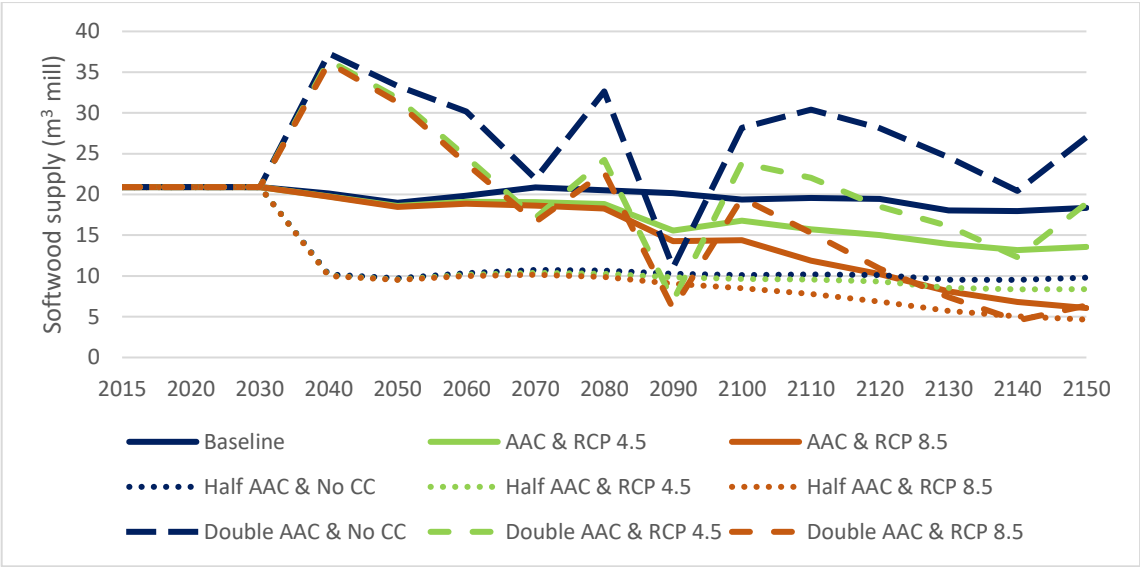

Figure 3.6 Aggregated supply of softwood in Québec from 2015-2150 (m^3 mill)

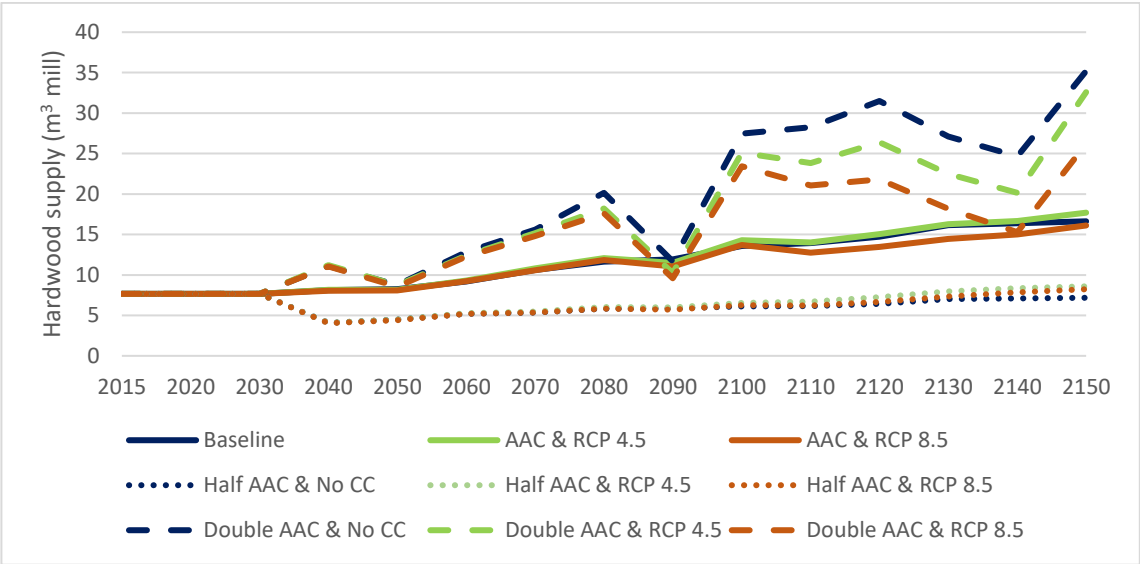

Figure 3.7 Aggregated supply of hardwood in Québec from 2015-2150 (m^3 mill)

As expected, altering the AAC has an immediate impact on the supply of both hardwood and softwood, with the impact being present across the temporal scope of the study. When the AAC is halved and there is no climate change (i.e., Half AAC & No CC) there is a 46%, and 57% reduction in the supply of softwood, and hardwood, respectively in 2150, compared to the baseline. Under Half AAC, climate change has a negative impact on the supply of softwood, with the largest reduction (75% at the year 2150) occurring under RCP 8.5. Meanwhile under Half AAC climate change has a marginal positive impact on hardwood supply, as the supply is 48% and 50%, lower under RCP 4.5 and RCP 8.5 respectively in 2150 when compared to the baseline.

When the AAC is doubled, and there is no climate change (Double AAC & No CC) there is an increase in the supply of both hardwood (112%) and softwood (47%) by 2150 when compared to the baseline AAC. As expected, when the AAC is doubled climate change has a strong negative impact on the supply of softwood in 2150, as the supply increases by 3% under RCP 4.5 and decreases by 65% under RCP 8.5. The supply of hardwood is also negatively affected by climate change under Double AAC, with the supply increasing by 96% under RCP 4.5 and 57% under RCP 8.5 compared to the baseline. Doubling the AAC also results in a noticeable softwood supply shortage in 2070, 2090 and 2140 across all climate change scenarios. This shortage extends to the supply of hardwood with a significant shortage occurring in 2090.

As evident in Figures 3.8 & 3.9, there is a strong interactive effect between the AAC rate and climate change. Specifically, as the harvesting rates intensify, climate change tends to have a more significant impact on wood supply. For example, consider

softwood supply (Figure 3.8) under the baseline AAC where there is a 67% difference in volume supply between No CC and RCP 8.5 at 2150. When the AAC is doubled the differences increases to 112%. Meanwhile when the AAC is halved the differences decreases to 28%.

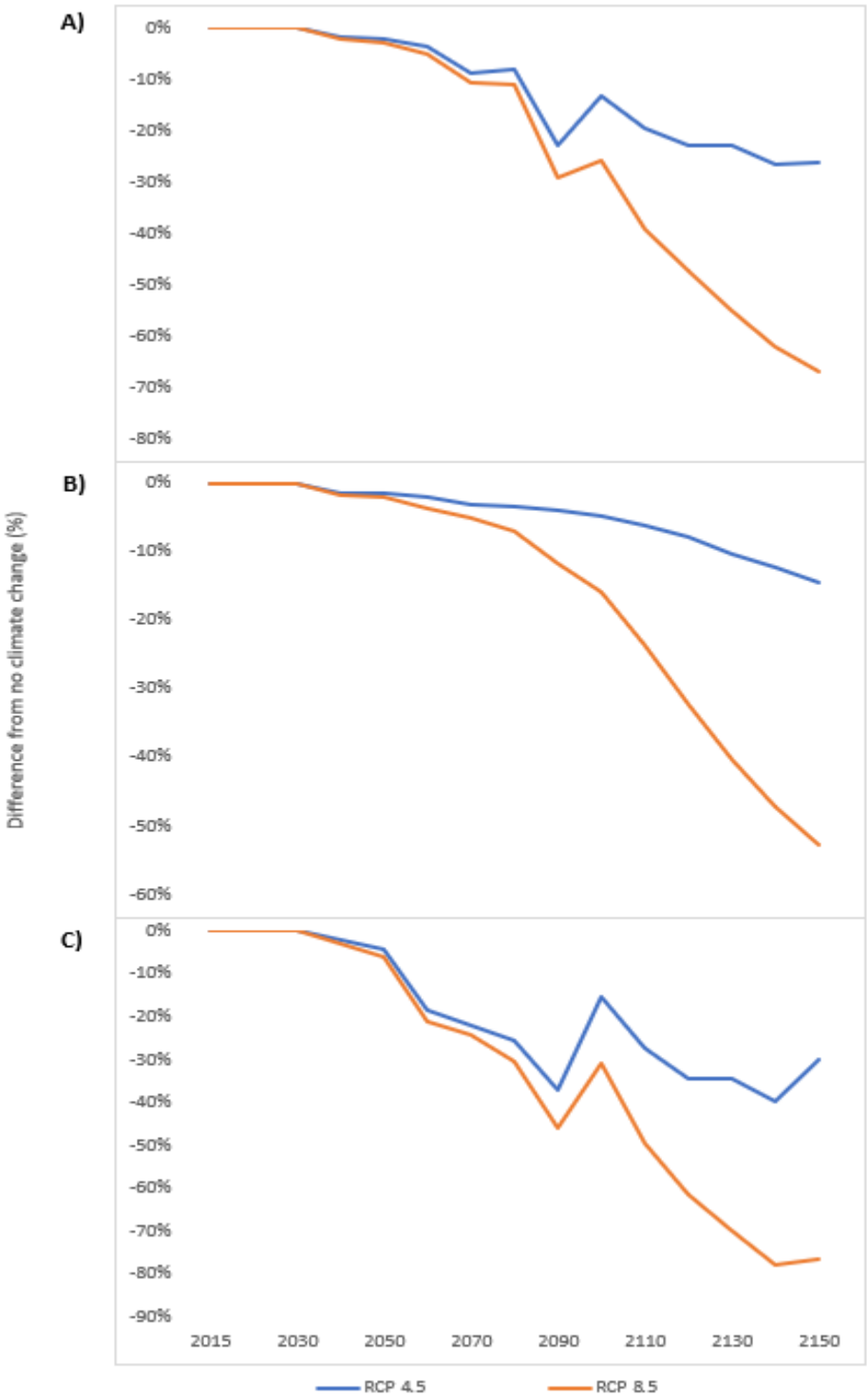

Figure 3.8 Differences in softwood supply under the two RCP scenarios compared to no climate change with (A) AAC, (B) Half AAC, and (C) Double AAC

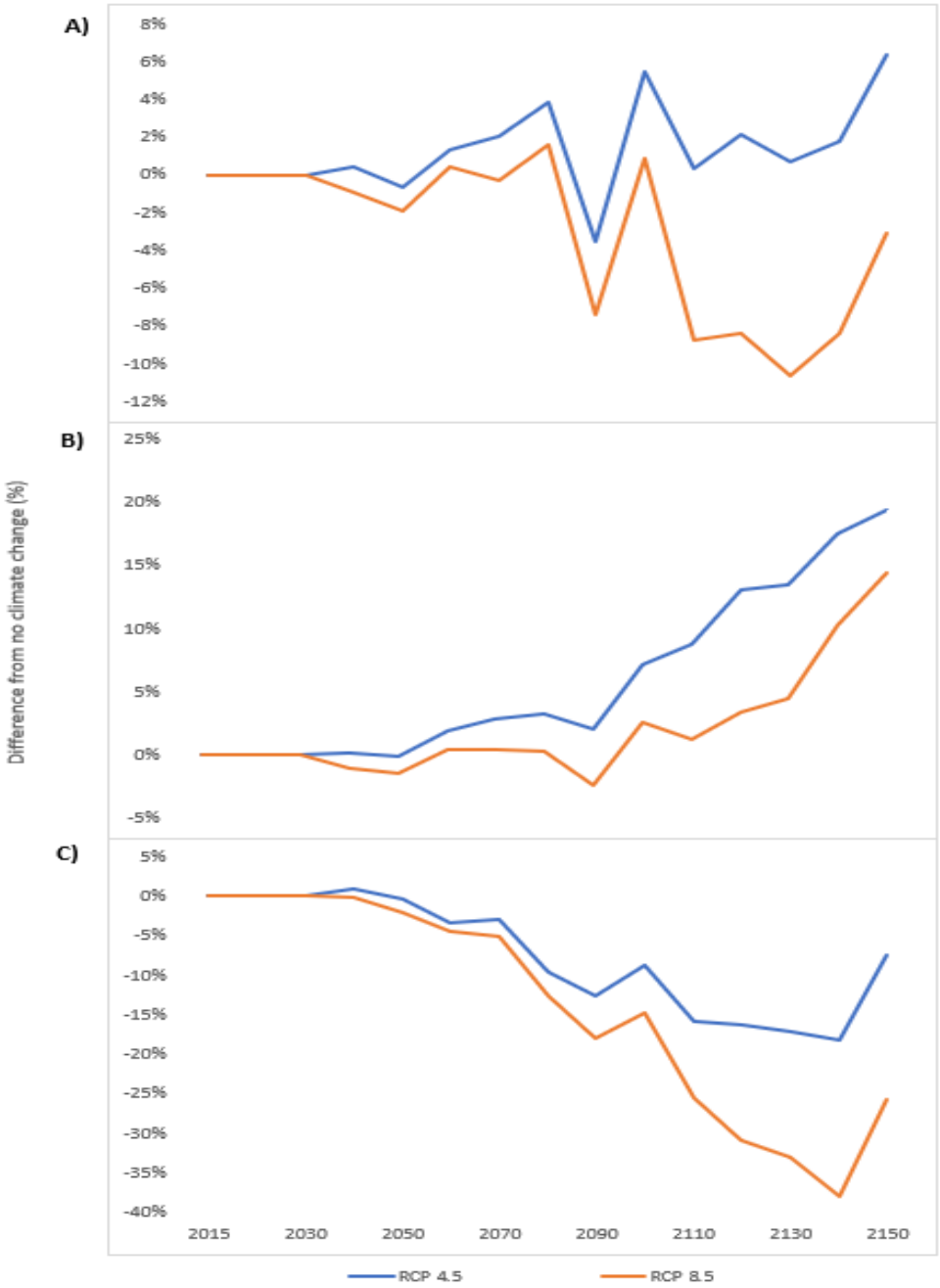

Figure 3.9 Differences in hardwood supply under the two RCP scenarios compared to no climate change with (A) AAC, (B) Half AAC, and (C) Double AAC

A similar interaction is evident for the supply of hardwood (Figure 9) as doubling the AAC increase the impact (54%) of climate change and halving the AAC results in climate change having a smaller impact (8%), when compared to the baseline AAC (9%). Furthermore, Figure 9 highlights how under the baseline AAC, RCP 4.5 results in an increase in hardwood supply. However, as climate change becomes more server (RCP 8.5) it starts to have a negative impact on hardwood supply. In comparison when the ACC is halved both climate scenarios result in an increase in hardwood wood supply by 2150 compared to the baseline. Meanwhile when the AAC is doubled climate change has a negative impact on the supply of hardwood, as under both RCP 4.5 and RCP 8.5 there is a reduction in supply compared to No CC.

3.4.2 Economic results

3.4.2.1 Sectoral impacts

Table 3.6 shows the value of output produced by individual sectors across all climate change and AAC scenarios. The value of output is determined by multiplying the quantity of output by the corresponding price. Furthermore, the price of H-FOR and S-FOR are heavily influenced by the stumpage price of hardwood (Figure 3.10) and softwood (Figure 3.11), respectively. Under the baseline AAC, climate change has a negative impact on the value of output from several forestry and wood-related sectors (S-FOR, SUPP, SAW-MANUF, VEN-MANUF, and PUP-MANUF), with the largest reduction in the value of output occurring under the most severe climate change scenario (RCP 8.5). As expected, S-FOR was the most sensitive to climate change, as the sector

experiences a reduction in the value of the output of 23% and 62% under AAC & RCP 4.5 and AAC & RCP 8.5 respectively, when compared to the baseline. Following the supply of hardwood, the H-FOR experiences a 6% increase in the value of output under AAC & RCP 4.5 when compared to the baseline. However, as climate change becomes more severe (RCP 8.5), the value of output decreases by -3% at 2150 compared to the baseline.

Table 3.6 Sectoral output value in Quebec by scenario in 2150 (% difference from the baseline)

Sectors	Scenarios								
	Baseline ($ mill)	AAC & RCP 4.5	AAC & RCP 8.5	Half AAC & No CC	Half AAC & RCP 4.5	Half AAC & RCP 8.5	Double AAC & No CC	Double AAC & RCP 4.5	Double AAC & RCP 8.5
CROP	16,418	0.25%	0.71%	0.70%	0.74%	0.97%	-0.81%	-0.29%	0.52%
S-FOR	1,947	-22.66%	-62.08%	-41.82%	-49.30%	-70.24%	36.84%	2.54%	-60.35%
H-FOR	716	5.75%	-3.18%	-52.02%	-44.25%	-46.33%	103.91%	89.10%	53.05%
FISH	413	0.16%	0.44%	0.43%	0.45%	0.59%	-0.50%	-0.17%	0.33%
SUPP	1,081	-6.56%	-18.67%	-17.55%	-18.96%	-24.87%	21.58%	8.61%	-13.24%
OILGAS	12,342	0.35%	0.99%	0.99%	1.05%	1.36%	-1.12%	-0.40%	0.73%
UTL	22,443	-0.08%	-0.20%	-0.23%	-0.23%	-0.28%	0.22%	0.03%	-0.18%
CONST	85,733	-0.01%	-0.05%	-0.06%	-0.06%	-0.08%	0.06%	0.03%	-0.03%
SAW-MANUF	5,380	-1.79%	-4.47%	-4.62%	-4.80%	-6.05%	4.79%	0.98%	-3.79%
VEN-MANUF	2,482	-1.55%	-3.85%	-3.89%	-4.07%	-5.15%	4.01%	0.76%	-3.32%
OW-MANUF	4,627	-0.25%	-0.62%	-0.64%	-0.67%	-0.84%	0.64%	0.12%	-0.53%
PUP-MANUF	9,651	-2.20%	-5.42%	-5.87%	-6.03%	-7.50%	6.07%	1.23%	-4.57%
CP-MANUF	5,201	-0.50%	-1.20%	-1.34%	-1.36%	-1.68%	1.29%	0.19%	-1.06%
PR-MANUF	3,917	0.01%	0.03%	0.01%	0.02%	0.03%	-0.04%	-0.03%	0.01%
OTH-MANUF	234,392	0.29%	0.81%	0.81%	0.86%	1.11%	-0.93%	-0.33%	0.60%
TRADES	49,806	0.02%	0.06%	0.05%	0.05%	0.07%	-0.06%	-0.02%	0.04%
RET	54,512	-0.02%	-0.06%	-0.07%	-0.07%	-0.09%	0.07%	0.04%	-0.04%
TRANSP	47,093	-0.12%	-0.33%	-0.32%	-0.35%	-0.44%	0.38%	0.13%	-0.25%
INFO	32,325	0.03%	0.08%	0.07%	0.08%	0.10%	-0.09%	-0.02%	0.07%
FIN	153,227	0.00%	-0.01%	-0.02%	-0.02%	-0.03%	0.02%	0.02%	0.00%
PROF	54,497	0.06%	0.17%	0.16%	0.17%	0.22%	-0.19%	-0.06%	0.13%
ADMIN	34,097	0.05%	0.15%	0.14%	0.15%	0.19%	-0.17%	-0.06%	0.11%
EDUC	1,689	0.00%	-0.02%	-0.03%	-0.03%	-0.04%	0.03%	0.02%	-0.01%
HEALTH	22,473	-0.01%	-0.04%	-0.05%	-0.05%	-0.07%	0.05%	0.03%	-0.02%
ENT	8,378	0.04%	0.10%	0.09%	0.09%	0.12%	-0.11%	-0.03%	0.08%
ACC	25,924	0.02%	0.06%	0.05%	0.05%	0.06%	-0.06%	-0.01%	0.05%
OG&S	31,454	-0.03%	-0.08%	-0.09%	-0.10%	-0.12%	0.10%	0.05%	-0.05%

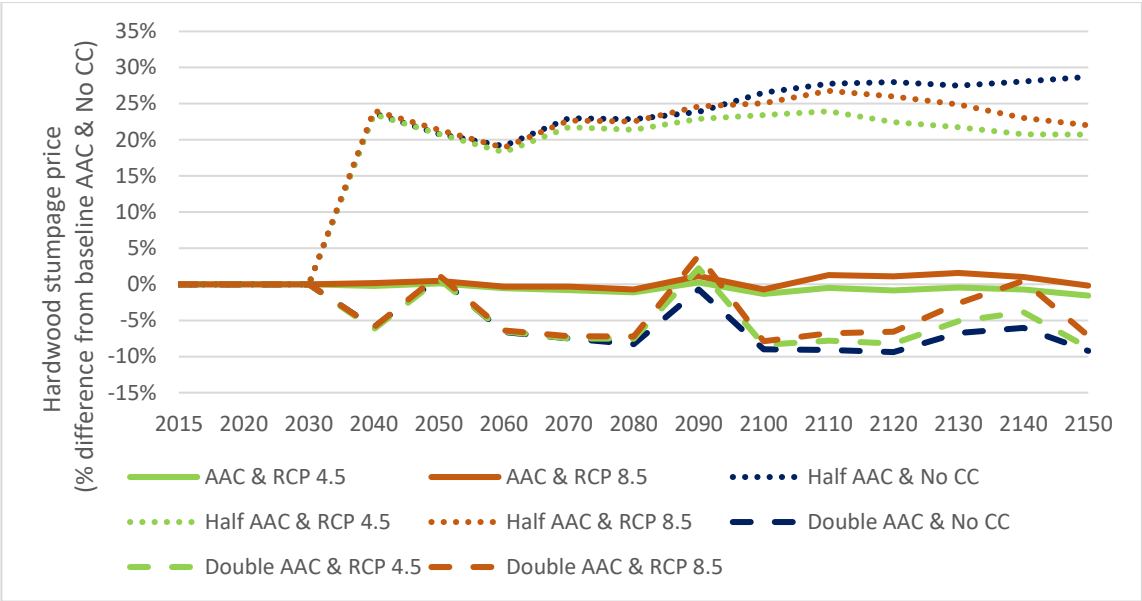

Figure 3.10 Hardwood stumpage prices in Québec (in % differences from the Baseline ACC & No CC**)**

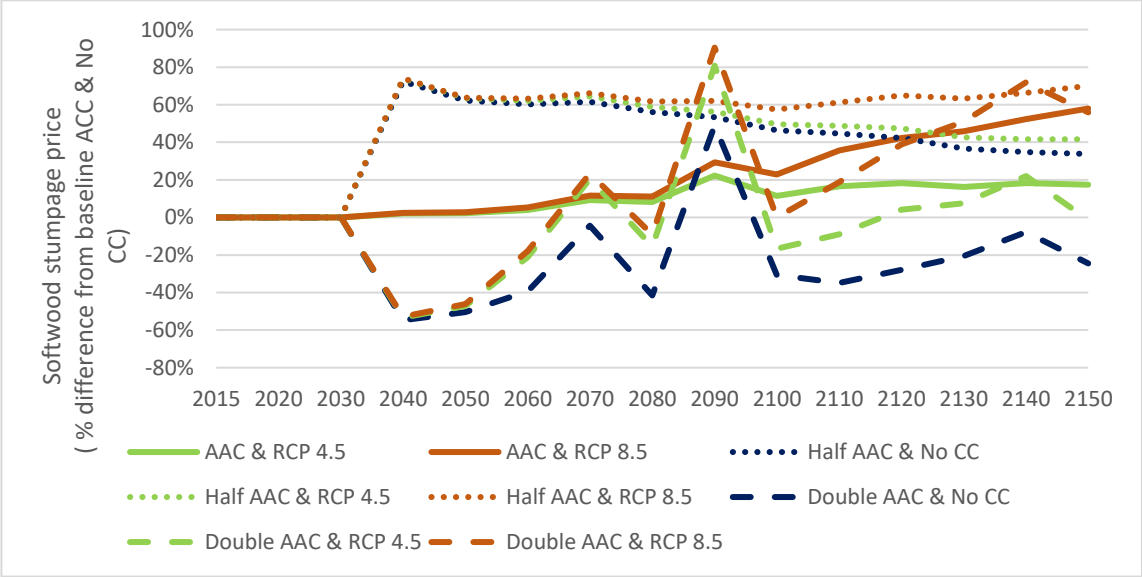

Figure 3.11 Softwood stumpage prices in Québec (in % differences from the Baseline ACC & No CC)

When the AAC is halved, and climate change is not accounted for (Half AAC & No CC) there is a reduction in output across all forestry and wood-related sectors, with S-FOR and H-FOR experiencing a 42% and 52% reduction in the value of output, respectively, compared to the baseline. Under Half AAC climate change has a negative impact on S-FOR as well as all wood-related manufacturing sectors. S-FOR experiences the largest reduction in the value of output across the whole economy, as the value of output decrease by 49% (Half AAC & RCP 4.5) and 70% (Half AAC & RCP8.5) at 2150, compared to the baseline. Meanwhile, climate change has a positive impact on the value of output from H-FOR as the value of output decreases by 44% (Half AAC & RCP 4.5) and 46% (Half AAC & RCP 8.5) at 2150 compared to the baseline. These reductions are less than what is seen under Half AAC & No CC (52.02%)

When the AAC is doubled, and climate change is not considered, there is an increase in the value of output across all forestry and wood-related sectors, compared to the baseline. H-FOR experiences the greatest increase (104%) the in value of output, followed by S-FOR (37%). Additionally, all wood manufacturing sectors experience a small increase in the value of output between 1% and 6%. Under Double AAC climate change has a negative impact on all forestry and wood-related sectors. S-FOR was the most susceptible to climate change with the sector experiencing a 2% increase in the value of output under Double AAC & RCP 4.5 and a 60% reduction in the value of output under Double AAC & RCP 8.5 at 2150. H-FOR experiences a similar trend as the sector sees an increase in the value of output of 89% and 53% under Double AAC & RCP 4.5 and Double AAC & RCP 8.5, respectively at 2150.

As the harvesting rate increases, so does the difference in the value between climate change scenarios. Under the baseline AAC the difference in the value of output between No CC and RCP 8.5 for H-FOR and S-FOR is 89% and 62.% respectively. Meanwhile, when the AAC is doubled, H-FOR and S-FOR experience a 51% and 98% difference in value between No CC and RCP 8.5, respectively. Reducing the AAC by half significantly reduced the difference in the value of output between the No CC and RCP 8.5 climate scenarios, to 28% (S-FOR) and 8% (H-FOR).

3.4.2.2 Macro-economic impacts

Table 3.7 presents the change in current value macroeconomic variables across scenarios, compared to the baseline scenario, at 2150. Under the baseline ACC, climate change has a relativity small impact on all macroeconomic variables. For instance, in 2150 GDP decreases by 0.02% under AAC & RCP 4.5 and 0.06% under ACC & RCP 8.5 compared to the baseline. Furthermore, at 2150 EV experiences a 0.05% and 0.18% reduction in value under RCP 4.5 and RCP 8.5 respectively, when compared to the baseline. The only macroeconomic variables that experience an increase in value are IMP (1.6% in AAC & RCP 4.5, and 0.44% in AAC & RCP 8.5) and EXP (0.16% in AAC & RCP 4.5, and 0.45% in AAC & RCP 8.5).

Table 3.7 Current value macro-economic variables in Quebec in 2150 (% difference from the baseline)

Variables[a]	Scenarios								
	Baseline ($ mill)	AAC & RCP 4.5	AAC & RCP 8.5	Half AAC & No CC	Half AAC & RCP 4.5	Half AAC & RCP 8.5	Double AAC & No CC	Double AAC & RCP 4.5	Double AAC & RCP 8.5
GDP	601,631	-0.02%	-0.06%	-0.07%	-0.07%	-0.10%	0.07%	0.04%	-0.04%
Y	570,429	-0.02%	-0.07%	-0.08%	-0.08%	-0.11%	0.08%	0.04%	-0.04%
EV	154,951	-0.05%	-0.18%	-0.21%	-0.22%	-0.28%	0.22%	0.11%	-0.10%
C	357,235	-0.02%	-0.07%	-0.08%	-0.08%	-0.11%	0.08%	0.04%	-0.04%
GC	189,445	-0.01%	-0.03%	-0.04%	-0.04%	-0.05%	0.02%	-0.01%	-0.03%
I	60,450	-0.02%	-0.07%	-0.08%	-0.08%	-0.11%	0.08%	0.04%	-0.04%
L	187,032	-0.01%	-0.03%	-0.04%	-0.04%	-0.05%	0.04%	0.00%	-0.03%
K	359,520	-0.01%	-0.03%	-0.04%	-0.04%	-0.05%	0.04%	0.01%	-0.02%
XD	922,218	-0.01%	-0.04%	-0.04%	-0.05%	-0.06%	0.05%	0.02%	-0.02%
XDD	618,447	-0.08%	-0.23%	-0.19%	-0.21%	-0.29%	0.16%	0.03%	-0.21%
IMP	314,246	0.16%	0.44%	0.34%	0.38%	0.53%	-0.27%	-0.03%	0.41%
EXP	300,549	0.16%	0.45%	0.35%	0.39%	0.54%	-0.27%	-0.03%	0.43%

[a] GDP = gross domestic product; Y = household income; EV = equivalent variation; C = household consumption; GC = government consumption; I = investment; L = value labour; K = value capital; XD = value of output consumed by the domestic market (including imports); XDD = output produced and consumed domestically; IMP = value of imports; EXP = value of exports.

Halving the ACC under the baseline climate (i.e., Half AAC & No CC) results in a small reduction in the value of several macroeconomic variables at 2150, including GDP (-0.07%), Y (-0.07%), EV (-0.21%), C (-0.07%), and I (-0.08%). The two macroeconomic variables that experience an increase in value are IMP (0.34%) and EXP (0.35%). As expected, climate change has a negative impact on most of the current value macroeconomic variables, with the largest impact occurring under RCP 8.5. The impact of climate change was most prominent in EV at 2150, as the value decreases by 0.22% under Half AAC & RCP 4.5 and 0.28% under Half AAC & RCP 8.5 when compared to the baseline. Meanwhile, climate change had a positive impact on the value of IMP (0.34% to 0.53%) and EXP (0.35% to 0.54%).

When the AAC is doubled, and climate change is not accounted for (i.e., Double AAC & No CC), there is a positive impact on all macroeconomic variables at 2150 with the exception of IMP and EXP. For instance, GDP (0.07%), Y (0.08%), EV (0.22%), C (0.08%), and I (0.08%) all experience a noticeable increase in value by 2150 when compared to the baseline. Meanwhile, IMP and EXP both decrease by 0.27% in value, compared to the AAC & No CC. Excluding IMP, EXP, and CG, climate change has a negative impact on all other macroeconomic variables when the AAC is doubled. For example, under Double AAC & RCP 4.5, GDP, Y, EV, C, and I experience an increase of 0.04%, 0.04%, 0.11%, 0.04% and 0.04% respectively, when compared to ACC & No CC. Meanwhile, IMP (0.03%) and EXP (0.03%) both experience a decrease in value of 0.03%. Under severe climate change (RCP 8.5) GDP (0.04%), Y (0.04%), EV (0.10%), C (0.04%), and I (0.04%) all experience a noticeable decrease in value compared to the

AAC & No CC. The two macroeconomic variables that experience a positive increase were IMP (0.41%) and EXP (0.43%).

Altering the AAC results in a change in differences between climate change scenarios at 2150. For instance, under the Baseline AAC, there is a 0.21% difference in the value of EV between No CC and RCP 8.5. Meanwhile, when the AAC is reduced by half the difference between climate scenarios is reduced to 0.07% for EV. Furthermore, when the AAC is doubled, the difference between macroeconomic variables across climate scenarios increases, with the most noticeable increase occurring in the value of EV 0.32%.

Table 3.8 highlights the change in cumulative present value (2% discount rate) macroeconomic variables by scenario, compared to the baseline. These variables follow a similar trend to the current value macroeconomic variables. Specifically, under the baseline AAC climate change has a negative impact on several variables, with the most sensitive being EV. Meanwhile, climate change has a positive impact on IMP and EXP, with the largest change in value occurring under the most severe climate scenario. Furthermore, reducing the AAC by half results in a significant impact on all macroeconomic variables, with climate change intensifying the impact. Doubling the AAC, on the other hand, causes a positive increase in all variables except for IMP and EXP, with climate change intensifying these impacts. As expected, climate change has the strongest impact on the economic variables under a double AAC. Meanwhile reducing the AAC by half results in a reduction in the strength of climate change impacting the macroeconomic variables.

Table 3.8 Cumulative present value macro-economic variables in Quebec by scenario in 2150 (% difference from the baseline; 2% discount rate)

Variables[a]	Scenarios								
	Baseline ($ mill)	AAC & RCP 4.5	AAC & RCP 8.5	Half AAC & No CC	Half AAC & RCP 4.5	Half AAC & RCP 8.5	Double AAC & No CC	Double AAC & RCP 4.5	Double AAC & RCP 8.5
GDP	2,316,490	-0.01%	-0.01%	-0.04%	-0.04%	-0.05%	0.03%	0.02%	0.01%
Y	2,239,513	-0.01%	-0.01%	-0.04%	-0.05%	-0.05%	0.03%	0.02%	0.01%
EV	147,803	-0.06%	-0.12%	-0.48%	-0.49%	-0.53%	0.33%	0.18%	0.08%
C	689,791	0.00%	0.00%	-0.02%	-0.02%	-0.02%	0.02%	0.01%	0.01%
GC	228,126	-0.01%	-0.01%	-0.04%	-0.04%	-0.05%	0.03%	0.02%	0.01%
I	718,587	-0.01%	-0.01%	-0.03%	-0.03%	-0.03%	0.03%	0.02%	0.01%
L	1,378,442	0.00%	-0.01%	-0.03%	-0.03%	-0.03%	0.02%	0.01%	0.01%
K	3,536,457	0.00%	-0.11%	-0.03%	-0.03%	-0.03%	0.02%	0.01%	0.01%
XD	3,536,457	0.00%	-0.01%	-0.03%	-0.03%	-0.03%	0.02%	0.01%	0.01%
XDD	2,641,542	-0.02%	-0.04%	-0.13%	-0.14%	-0.15%	0.07%	0.03%	0.00%
IMP	1,016,781	0.05%	0.09%	0.30%	0.31%	0.34%	-0.16%	-0.06%	0.00%
EXP	953,463	0.05%	0.10%	0.31%	0.32%	0.35%	-0.16%	-0.06%	0.01%

[a] GDP = gross domestic product; Y = household income; EV = equivalent variation; C = household consumption; GC = government consumption; I = investment; L = value labour; K = value capital; XD = value of output consumed by the domestic market (including imports); XDD = output produced and consumed domestically; IMP = value of imports; EXP = value of exports.

3.5 Discussion

3.5.1 Climate and harvesting effects on forest dynamics

In this study, climate change is found to have a strong impact on Québec's forest dynamics, with severe climate change driving highly discernible decreases in the abundance of cold-adapted softwood species (e.g., balsam fir, white and black spruce, tamarack, jack pine, cedar, and eastern hemlock). These projections well align with previous studies (Boulanger et al., 2019, 2022; Boulanger & Pascual Puigdevall, 2021; Brecka et al., 2020; Taylor et al., 2017) are considered largely a consequence of cold-adapted softwood species becoming maladapted to a future warmer climate.

However, the reduction in the abundance of currently dominant cold-adapted softwood species under climate change did not directly result in an increase in the abundance of warm-adapted hardwood species (e.g., red maple, American beach, and white birch), especially in the northern forest areas (boreal forest east and west). This is likely due to established cold-adapted boreal species "blocking" the recruitment and growth of warm-adapted species, by pre-empting space and limiting the availability of light, nutrients, and water (Taylor et al., 2017). This blocking effect results in a lag (Bertrand et al., 2011; Zhu et al., 2014) in the migration and establishment of warm-adapted species better suited to the warming climate.

This study also found, as expected, that altering the AAC has a strong effect on forest dynamics. Specifically, reducing the AAC results in an increase in mean above-ground biomass in all forest areas. This is the result of the reduction in AAC lowering the disturbance rate within the forest. The opposite is true - an increase in AAC results

in a decrease in mean above-ground biomass. Early succession species (e.g., white birch, aspen, and red maple) are the least impacted by the increase in AAC due to them having a competitive advantage in re-establishing themselves after a large-scale disturbance such as clear cutting (Fei & Steiner, 2009; Maleki et al., 2021). However, the impact on early succession species would likely vary if the scenarios tested within this study incorporated replanting options; specifically, options that target economic important softwood species such as spruces and pines.

The interaction between climate change and harvesting activities aligns with previous literature (e.g., Boulanger et al., 2019; Brecka et al., 2020 Taylor et al., 2017) as well as our initial hypothesis, in that an increase in AAC will exacerbate the impact of climate change on the forest structure. This is due climate change increasing the disturbances rate within the forest through large scale events such as forest fires and droughts. The disturbance rate is further intensified as harvesting activities increase. Furthermore, harvesting activities have been shown to increase the disturbance level of the Eastern Boreal Forest to an extended that is greater than what is seen under natural variability (Cyr et al., 2009).

Where our results differ from previous studies, including Brecka et al. (2020), is that we find that reducing the AAC under severe climate change results in a larger decrease in wood supply compared to when the AAC is increased under serve climate change. The difference in findings is likely due to both the temporal of the study as well as the harvesting scenarios used within this study. For instances using hypothetical harvesting scenarios that are closer to the baseline AAC (e.g., 75% AAC, or 1.25% AAC)

would reduce the impact altering the AAC has on the forest structure. Furthermore, AAC scenarios that more closely align with the baseline AAC would result in climate change having a greater impact on the forest compared to altering the AAC, which is what is seen in Brecka et al. (2020). Extending the temporal scope of this study (2020-2150) to the one used in Brecka et al. (2020, 2020-2220) would result in the study capturing addition climate change effects, especially in later years as the intensity of climate change increase. As such Adjusting either the temporal scope or the harvesting scenarios may result in climate change being the main driver of change in forest structure.

3.5.2 Forest dynamics and wood supply

As expected, a change in forest dynamics has a significant impact on both the volume of biomass harvested as well as the aggregate wood supply. The two drivers of change that are accounted for in this study (i.e., climate change and the AAC) have varying degrees of impact on the provincial wood supply. For instance, increasing anthropogenic climate forcing has a negative impact on forest structure, volume of biomass harvested of individual species, and aggregated softwood. This is expected as studies have shown that climate change has a negative impact on both forest structure (Boulanger et al. 2017), as well as forest services including wood supply (Brecka et al, 2020, McMonagle et al. 2022). Hardwood supply was the only ecological indicator that was not always negatively impacted by climate change. As the directional impact of

climate change on hardwood supply was dependent on both the severity of climate change as well as the AAC scenario.

Meanwhile the impact on forest dynamics caused by altering the AAC delivers a trade-off between forest structure and supply of hardwood and softwood. Specifically, reducing the AAC has a positive impact on forest dynamics by reducing the disturbances within the forest for the trade-off of reducing wood supply. Likewise, the opposite is true, as increasing the AAC results in an increase in wood supply for the trade-off of negativity impacting forest structure. These trade-offs become more complex when accounting for climate change, as not only does a change in AAC impact the current forest structure but it also impacts the vulnerability of the forest to be negatively impacted by climate change. Specifically, as decreasing the AAC results in a smaller difference in wood supply across climate scenarios. Likewise, increasing the AAC increases the differences in volume of wood supply between the three climate change scenarios. This aligns with Brecka et al. (2020) and Raulier et al. (2014) who suggest that reducing the AAC could provide the forest with a buffer for being negatively impacted by large scale disturbance, such as forest fire.

Hence, from an ecological perspective that aims at preserving the forest, it makes sense to introduce policies that lowers the AAC, as not only does it directly increase the above ground biomass within the forest, but it also decreases the intensity in which climate change will impact both the biomass of individual species, as well as the aggregated wood supply. However, there needs to be consideration how the

change in wood supply will impact forestry and wood related sectors, as well as well as the economy as a whole.

3.5.3 Macro-economic variables

The relatively small economy-wide impacts found in this study from altering harvesting rates and climate change are due to the size of the forestry and wood-related sectors with respect to the provincial economy. For instance, as of 2015, the forestry and wood-related sectors in Québec account for less than 1% of the provincial GDP (Statistics Canada, 2021a). Hence, even though the forestry and wood-related sectors experience a large change in the value of output (-70% to 104%), the provincial GDP undergoes only minor changes (-0.1% to 0.07%). The change in macroeconomic variables will likely be felt disproportionately across the provinces as the 40 forestry-dependent communities in Québec (Statistics Canada, 2018), will likely experience the larger impact compared to communities that have a more diverse economy.

Throughout the results, there are two macro-economic variables (IMP and EXP) that experience an inverse change in value when compared to other macro-economic variables. Initially, it seems counterintuitive for EXP to increase while GDP and Y decrease. However, the increase is the result of one of the market closures used within this CGE model. Specifically, with foreign savings fixed, an increase in IMP requires an increase in EXP to ensure that the foreign market is cleared. This has been seen in other economic studies that have used a similar CGE mode (Lantz et al. 2022, and

McMonagle et al. 2023), as foreign savings is a variable that is typically fixed in single region recursive dynamic CGE models (Lofgren et al., 2002).

Furthermore, a change in the supply of softwood is significantly more impactful on the economy, relative to a comparable change the in the supply of hardwood. This is largely due to softwood being economically more important than hardwood, as sectors have more of a demand for S-FOR outputs instead of H-FOR. This is seen in today's market with softwood making up 78% of total wood harvested in Québec (CCFM, 2020a) along with typically selling for a higher price than hardwood (Québec's Bureau de mise en Marchè des bois, 2017).

There are also several sectors (CROP, FISH, OILGAS and OTH-MANUF) that experience an increase in the value of output under a reduction in the supply of softwood. The increase in the value of output is likely the result of the redistribution of capital and labour within the economy (away from impacted sectors and towards non-impacted sectors), in addition to the increase in EXP. Similarly, when there is an increase in the supply of softwood (Double AAC & No CC, and Double ACC & RCP 4.5), the sectors mentioned above experience a reduction in value of output.

The economic results from this study differ from both Ochuodho and Lantz (2014) and Boccanfuso et al. (2018) due to the differences in structure of the CGE models along with how each study determines the impact of climate change. For instance, Ochuodho and Lantz (2014) predicted a 0.098% (low climate change) to 0.061% (high climate change) increase on cumulative present value (4% discount rate)

GDP between 2006-2051 using a single regional CGE model. In their study, low climate change results in a 2.6% increase in wood supply, while high climate change results in a 6.5% reduction. Boccanfuso et al. (2018), on the other hand finds that GDP experiences a 0.12% reduction in value by 2050. While our findings are closer to Boccanfuso et al. (2018) the temporal scope of the studies make comparing results difficult. However, we contend again here that our estimates are more robust than both Ochuodho and Lantz (2014) and Boccanfuso et al. (2018). Specifically, our analysis is based on wood supply estimates generated from an ecological model rather than from previous literature or expert opinion.

3.5.4 Economics of a changes in forest dynamics

As previously mentioned, our findings contradict recently published forest landscape studies (e.g., Brecka et al., 2020) that suggest reducing harvesting rates will improve the economic of the forestry sector. Indeed, our findings indicate that while halving the AAC reduces the negative impact of climate change on forest dynamics and wood supply, the value of this benefit is overshadowed by the reduced timber harvest value and economic activity that results. While the contradicting ecological findings may be driven by different assumptions each study makes regarding the time horizon and harvesting scenarios, there are addition economic factors that may reinforce the contradiction. For instance, future values are treated differently in economic studies when compared to traditional forest landscape studies. This is due to economic studies routinely examine the extent of the impact using cumulative present values which

requires discounting future values. When future values are discounted they will have a smaller impact on the cumulative present value when compared to values that occur earlier on. This is especially important as changing the harvesting rates have an immediate impact, while the effects of climate change are felt much later. As such, a decrease in the AAC in the near term will have a significant impact on the cumulative present value, whereas a similar increase in AAC in the distant future (or a reduced negative impact of climate change on the AAC) would have a very small impact the cumulative present value. This is also one of the reasons why the wood supply shortages under Double AAC in the years 2070, 2090 and 2140 do not have a significant impact on the cumulative present value macroeconomic variables seen in Table 8.

Additionally, traditional forest landscape studies do not typically consider how a short-term change in AAC will alter the growth rate of the economy over time. Economic studies, such as this one, account for this using a capital accumulation formula. As such, halving/doubling the AAC results in a marginally slower/faster growth rate compared to the baseline. Initially, the differences in growth rates are relativity small and as such do not play a significant role in the difference in economic variables under different scenarios. However, by 2150, the differences in growth rates cause a significant gap in current values between harvesting scenarios. This explains whys the current macroeconomic variables are larger under Double AAC & RCP 4.5 compared to AAC & RCP 4.5 even though by 2150 both scenarios have similar softwood supplies.

It is important to note that, although doubling the wood supply in our analysis results in an increase in many economic variables, it may also result in losses of other

forest ecosystem service values that we haven't captured in our analysis. Examples of such services include watershed protection, wildlife habitat and carbon sequestration, all of which have been shown to be impacted by a change in harvest activities (Hume et al., 2018; Law et al., 2018; Malcolm et al., 2020; Parolari & Porporato, 2016; Popescu & Hunter, 2011; St-Laurent et al., 2022). Accounting for changes in these ecosystem services and their associated values may change the economic results as the monetary benefit gained by increasing AAC may be outweighed by the ecosystem service value losses.

3.5.5 Limitations

There are several limitations of the PICUS-LANDIS-CGE framework that should be noted. First, the study does not contain any specific forest management strategy outside of altering the AAC. For instance, we do not consider how planting and thinning would impact either forest structure or wood supply. Furthermore, the AACs we use in the study do not use optimal scheduling to maximize and stabilize wood supply.

Second, the models in this study are deterministic in nature, and as such, they require parameters to calibrate to the study area. Although the parameters are based on published literature, they may not capture all the interactions that are occurring within the study area. For instance, although the fire parameters are calibrated for various climate change scenarios, they may not represent the current landscape that is being described by LANDIS as it does not account for the organic build-up and forest

fire mitigation strategies. Additionally, the parameters for SBW are not sensitive to climate change, however, we validate this by assuming any decrease in biomass lost to SBW outbreaks (Gray, 2013; Régnière et al., 2012) would be offset by the increase in the abundance of insects and diseases that are currently restricted by cold weather, such as the hemlock woolly adelgid (*Adelges tsugae,* Paradis et al., 2008).

Third, the CGE parameters and elasticities that simulate sector and agent preferences are based on the national average, and hence, they may differ from current and future preferences within Québec.

Lastly, Québec's forests make up a significant proportion of both Canada's and the world's forests. Hence, under severe climate change, Québec will likely not be able to import additional forestry and wood-related goods into the economy, as the rest of the world will also be experiencing a change the in quantity and composition of wood supply. As such, the economic impact of severe climate may be greater than what is shown in this study.

3.6 Conclusion

The findings from this study provide a unique insight into how climate change and harvesting rates interact with each to affect Québec's forest, wood supply, forest sector and the overall economy. We found that although halving the current AAC reduces the impact of climate change on the forest landscape, it also leads to a significant reduction in wood supply, and a negative impact on the economy under all climate change scenarios. Meanwhile, doubling the AAC results in opposite outcomes.

The findings of this study highlight the need for future CGE studies that examine the economic impacts of changes in both market (e.g., wood products) and non-market (e.g., biodiversity, watershed protection, carbon storage) forest services. Indeed recent literature points to means through which systems of environmental and economic accounts (Ochuodho & Alavalapati, 2016) or social prices[31] can be used to conduct such analyses. Incorporating market and non-market forest services into this analysis would allow for a further improvement in our understanding of the socio-economic impacts of climate change and appropriate mitigation strategies to protect forests from climate change in the future.

[31] The social price is the sum of the market price and the cost of any externalities (positive or negative) associated with the good/services.

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3.8 Appendix

Table A1. Sectoral output prices (% difference from the baseline) in 2150

Sectors	Scenarios							
	AAC & RCP 4.5	AAC & RCP 8.5	Half AAC & No CC	Half AAC & RCP 4.5	Half AAC & RCP 8.5	Double AAC & No CC	Double AAC & RCP 4.5	Double AAC & RCP 8.5
CROP	0.01%	0.02%	0.02%	0.02%	0.03%	-0.02%	0.00%	0.01%
S-FOR	3.41%	11.16%	6.55%	8.07%	13.44%	-4.88%	-0.25%	10.76%
H-FOR	-0.54%	-0.06%	9.64%	6.99%	7.43%	-3.23%	-3.07%	-2.47%
FISH	0.00%	0.01%	0.01%	0.01%	0.01%	-0.01%	0.00%	0.01%
SUPP	0.00%	0.01%	0.01%	0.01%	0.01%	-0.01%	0.00%	0.01%
OILGAS	0.00%	0.01%	0.01%	0.01%	0.02%	-0.01%	0.00%	0.01%
UTL	0.00%	0.01%	0.01%	0.01%	0.02%	-0.01%	0.00%	0.01%
CONST	0.03%	0.07%	0.08%	0.08%	0.10%	-0.07%	-0.01%	0.06%
SAW-MANUF	0.69%	1.79%	1.80%	1.89%	2.42%	-1.76%	-0.39%	1.50%
VEN-MANUF	0.34%	0.88%	0.89%	0.93%	1.19%	-0.88%	-0.19%	0.74%
OW-MANUF	0.26%	0.66%	0.66%	0.70%	0.89%	-0.67%	-0.14%	0.55%
PUP-MANUF	0.17%	0.45%	0.48%	0.50%	0.63%	-0.47%	-0.11%	0.37%
CP-MANUF	0.13%	0.32%	0.34%	0.35%	0.44%	-0.34%	-0.07%	0.26%
PR-MANUF	0.08%	0.20%	0.22%	0.23%	0.28%	-0.22%	-0.05%	0.17%
OTH-MANUF	0.01%	0.02%	0.03%	0.03%	0.04%	-0.03%	0.00%	0.02%
TRADES	0.00%	0.00%	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%
RET	0.00%	0.00%	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%
TRANSP	0.00%	0.00%	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%
INFO	0.00%	0.01%	0.01%	0.01%	0.02%	-0.01%	0.00%	0.01%
FIN	0.00%	0.00%	0.01%	0.01%	0.00%	0.00%	0.00%	0.00%
PROF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
ADMIN	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
EDUC	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
HEALTH	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
ENT	0.00%	0.00%	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%
ACC	0.00%	0.01%	0.01%	0.01%	0.01%	-0.01%	0.00%	0.01%
OG&S	0.00%	0.00%	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%

Table A2. Sectoral output (% difference from the baseline) in 2150

Sectors	Scenarios								
	Baseline ($ mill)	AAC & RCP 4.5	AAC & RCP 8.5	Half AAC & No CC	Half AAC & RCP 4.5	Half AAC & RCP 8.5	Double AAC & No CC	Double AAC & RCP 4.5	Double AAC & RCP 8.5
CROP	16,406	0.26%	0.71%	0.71%	0.75%	0.97%	-0.81%	-0.29%	0.52%
S-FOR	1,771	-25.20%	-65.88%	-45.38%	-53.08%	-73.76%	43.84%	2.80%	-64.20%
H-FOR	736	6.33%	-3.11%	-56.23%	-47.88%	-50.02%	110.66%	95.07%	56.95%
FISH	415	0.16%	0.45%	0.44%	0.47%	0.60%	-0.51%	-0.17%	0.34%
SUPP	1,083	-6.55%	-18.66%	-17.55%	-18.95%	-24.86%	21.57%	8.60%	-13.24%
OILGAS	12,301	0.36%	1.00%	1.00%	1.06%	1.37%	-1.13%	-0.41%	0.73%
UTL	22,260	-0.08%	-0.19%	-0.22%	-0.22%	-0.27%	0.21%	0.03%	-0.17%
CONST	85,783	-0.04%	-0.10%	-0.11%	-0.12%	-0.15%	0.12%	0.04%	-0.07%
SAW-MANUF	5,235	-2.46%	-6.12%	-6.28%	-6.55%	-8.25%	6.64%	1.37%	-5.20%
VEN-MANUF	2,449	-1.88%	-4.67%	-4.72%	-4.94%	-6.24%	4.92%	0.95%	-4.01%
OW-MANUF	4,583	-0.50%	-1.25%	-1.28%	-1.33%	-1.69%	1.30%	0.26%	-1.06%
PUP-MANUF	9,569	-2.36%	-5.82%	-6.30%	-6.48%	-8.05%	6.55%	1.34%	-4.91%
CP-MANUF	5,176	-0.62%	-1.49%	-1.65%	-1.69%	-2.08%	1.62%	0.26%	-1.30%
PR-MANUF	3,910	-0.07%	-0.15%	-0.18%	-0.19%	-0.22%	0.16%	0.01%	-0.14%
OTH-MANUF	234,101	0.29%	0.81%	0.81%	0.85%	1.10%	-0.92%	-0.33%	0.59%
TRADES	49,795	0.03%	0.07%	0.07%	0.07%	0.09%	-0.08%	-0.02%	0.06%
RET	54,631	-0.01%	-0.04%	-0.05%	-0.05%	-0.07%	0.05%	0.03%	-0.02%
TRANSP	47,125	-0.12%	-0.32%	-0.31%	-0.33%	-0.43%	0.36%	0.12%	-0.24%
INFO	32,263	0.03%	0.09%	0.08%	0.08%	0.11%	-0.10%	-0.02%	0.07%
FIN	153,175	0.00%	0.00%	-0.01%	-0.01%	-0.01%	0.00%	0.01%	0.01%
PROF	54,661	0.07%	0.19%	0.18%	0.19%	0.25%	-0.21%	-0.07%	0.15%
ADMIN	34,161	0.06%	0.17%	0.16%	0.17%	0.22%	-0.19%	-0.06%	0.13%
EDUC	1,693	0.00%	0.00%	-0.01%	-0.01%	-0.02%	0.01%	0.01%	0.01%
HEALTH	22,532	0.00%	-0.02%	-0.03%	-0.03%	-0.04%	0.03%	0.02%	-0.01%
ENT	8,401	0.05%	0.12%	0.10%	0.11%	0.14%	-0.12%	-0.03%	0.10%
ACC	25,969	0.03%	0.07%	0.06%	0.06%	0.08%	-0.07%	-0.01%	0.06%
OG&S	31,555	-0.02%	-0.07%	-0.07%	-0.08%	-0.10%	0.08%	0.04%	-0.04%

Table A3. Parameters used within the CGE model

Parameters	Discerption
Elasticities	
$\boldsymbol{\sigma F2_i}$	Substitution between factors (capital-labour bundle, hardwood stumpage, and softwood stumpage) within the second nest of the production function
$\boldsymbol{\sigma F3_i}$	Substitution between factors (capital and labour) within the third nest of the production function
$\boldsymbol{\sigma T_i}$	CET substitution between domestic market and the export market
$\boldsymbol{\sigma A_i}$	Arrington substation between domestic commodities and imported commodities
Share parameters	
$\boldsymbol{\gamma KL2_i}$	Share parameter for capital-labour bundle in the second nest of the production function
$\boldsymbol{\gamma TH2_i}$	Share parameter for hardwood stumpage in the second nest of the production function
$\boldsymbol{\gamma TS2_i}$	Share parameter for softwood stumpage in the second nest of the production function
$\boldsymbol{\gamma F3_i}$	Share parameter for the third nest of the production function the third nest
$\boldsymbol{\gamma T_i}$	Share parameter of the CET function and the destination of domestically produced commodities
$\boldsymbol{\gamma A_i}$	Share parameter of the Arrington function
Efficiency parameters	
$\boldsymbol{\lambda F1_i}$	Efficiency parameter for the factors of production (stumpage-capital-labour) in the first nest of the production function.
$\boldsymbol{\lambda F2_i}$	Efficiency parameter for the factors of production (capital-labour bundle, hardwood stumpage, and softwood stumpage) in the second nest of the production function.
$\boldsymbol{\lambda F3_i}$	Efficiency parameter for the factors of production (capital and labour) in the third nest of the production function.
$\boldsymbol{\lambda A_i}$	efficiency parameter in the Arrington function
$\boldsymbol{\lambda T_i}$	Shift parameter in the CET function
Tax rates	
tc_i	Tax rate on commodities consumed by the households
tk_i	Tax rate on capital
tl_i	Tax rate on labour
tY	Tax rate on household income
Tm_i	Tariff rate on imported commodities
Others	
$\boldsymbol{\alpha HLES_i}$	Power in the nested ELES household utility function
$\boldsymbol{\alpha KG}$	Cobb-Douglass power in the government's capital demand function
$\boldsymbol{\alpha LG}$	Cobb-Douglass power in the government's labour demand function
$\boldsymbol{\alpha CG_i}$	Cobb-Douglass power in the government's commodity demand function
$\boldsymbol{\alpha I_i}$	Cobb-Douglass power in the bank's commodity demand function
trep	Replacement rate
$io_{i,j}$	Technical coefficient of intermediate input
$\boldsymbol{\varphi}$	Philips curve parameter
$\boldsymbol{\mu H}$	Households subsistence consumption level
mps	Households marginal propensity to save
Growth rates	
GRL	Growth rate of labour
$\boldsymbol{\psi}$	Initial real rate of return

Table A4. Variables used within the CGE model

Variables	Description
Production block	
$WKL_{i,t}$	Stumpage-capital-labour bundle
$KL_{i,t}$	Capital-labour bundle
$TH_{i,t}$	Hardwood stumpage demand
$TS_{i,t}$	Softwood stumpage demand
$K_{i,t}$	Capital demand
$L_{i,t}$	Labour demand
$X_{i,t}$	Domestic sales of composition commodities
$XD_{i,t}$	Domestic produced of commodities (outputs)
$XDD_{i,t}$	Domestically produced commodities sold to the domestic market
$PWKL_{i,t}$	Price of stumpage-capital-labour bundle
$PKL_{i,t}$	Price of capital-labour bundle
PTH_t	Price of hardwood stumpage
PK_t	Price of capital (Rent)
PL_t	Price of labour (wages)
$P_{i,t}$	Price of composition commodities sold in
$PD_{i,t}$	Price of domestically produced commodities
$PD_{i,t}$	Price of domestically produced commodities
$PDD_{i,t}$	Price of commodities sold to the domestic market
$PD_{i,t}$	Price of domestically produced commodities
Household block	
Y_t	Household's income
$CBUD_t$	Household's expenditure
C_t	Household's demand for commodities
$PCINDEX_t$	Consumer price index
Factor supply	
LS_t	Labour supply (endowment)
KS_t	Capital supply (endowment)
TSS_t	Softwood stumpage supply (endowment)
THS_t	Hardwood stumpage supply (endowment)

Variables	Description
Investment block	
S_t	Total saving
SF_t	Forging savings
SG_t	Government's savings
$I_{i,t}$	Investment demand
Trade block	
$E_{i,t}$	exports of commodities
$M_{i,t}$	Imports of commodities
$PE_{i,t}$	Domestic price of exports
$PM_{i,t}$	Domestic price of imports
ER_t	Exchange rate
Government block	
LG_t	Government's demand for labour
KG_t	Government's demand for capital
$GC_{i,t}$	Government's demand for commodities
$TAXR_t$	Total taxes
TRF_t	Total transfer from the government to the household
TRO_t	Other transfers from the government to the household
$UNEMP_t$	economy wide unemployment
Dynamic Variables	
$GRSS_t$	Growth rate of softwood stumpage
$GRHS_t$	Growth rate of hardwood stumpage
RRR_t	Real rate of return

Table A5. Equations used in the CGE model

Equations		Description
Production block		
$\mathbf{WKL_{i,t} = \lambda F1_i * XD_{i,t}}$	EQ 1.1	Firms' demand for stumpage-capital-labour bundle (1st nest)
$\boldsymbol{PD_{i,t} * XD_{i,t} = (PWKL_{i,t} * WKL_{i,t}) + \left(\sum_j io_{j,i} * XD_{i,t} * P_{i,t}\right)}$	EQ 1.2	Firms' zero profit condition (1st nest)
$\mathbf{KL_{i,t}} = \frac{\mathbf{WKL_{i,t}}}{\mathbf{\lambda F2_i}} * \left(\frac{\boldsymbol{\gamma KL2_i}}{\boldsymbol{PKL_{i,t}}}\right)^{\boldsymbol{\sigma F2_i}} * \left[\left(\boldsymbol{\gamma KL_i^{\sigma F2_i} * PKL_{i,t}^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TS_i^{\sigma F2} * PTS_t^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TH_i^{\sigma F2} * PTH_t^{(1-\sigma F2_i)}}\right)\right]^{\left(\frac{\boldsymbol{\sigma F2_i}}{\boldsymbol{(1-\sigma F2_i)}}\right)}$	EQ 1.3	Firms' demand for capital-labour bundle
$\mathbf{TH_{i,t}} = \frac{\mathbf{WKL_{i,t}}}{\mathbf{\lambda F2_i}} * \left(\frac{\boldsymbol{\gamma TH2_i}}{\boldsymbol{PTH_t}}\right)^{\boldsymbol{\sigma F2_i}} * \left[\left(\boldsymbol{\gamma K_i^{\sigma F2_i} * PKL_{i,t}^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TS_i^{\sigma F2} * PTS_t^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TH_i^{\sigma F2} * PTH_t^{(1-\sigma F2_i)}}\right)\right]^{\left(\frac{\boldsymbol{\sigma F2_i}}{\boldsymbol{(1-\sigma F2_i)}}\right)}$	EQ 1.4	Firms' demand for hardwood stumpage (2nd nest)
$\mathbf{TS_{i,t}} = \frac{\mathbf{WKL_{i,t}}}{\mathbf{\lambda F2_i}} * \left(\frac{\boldsymbol{\gamma TS2_i}}{\boldsymbol{PTS_t}}\right)^{\boldsymbol{\sigma F2_i}} * \left[\left(\boldsymbol{\gamma KL_i^{\sigma F2_i} * PKL_{i,t}^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TS_i^{\sigma F2} * PTS_t^{(1-\sigma F2_i)}}\right) + \left(\boldsymbol{\gamma TH_i^{\sigma F2} * PTH_t^{(1-\sigma F2_i)}}\right)\right]^{\left(\frac{\boldsymbol{\sigma F2_i}}{\boldsymbol{(1-\sigma F2_i)}}\right)}$	EQ 1.5	Firms' demand for softwood stumpage (2nd nest)
$\mathbf{PWKL_{i,t} * WKL_{i,t}} = \boldsymbol{\left((PKL_{i,t} * KL_{i,t}) + (PTH_t * TH_{i,t}) + (PTS_t * TS_{i,t})\right)}$	EQ 1.6	Firms' zero profit condition (2nd nest)

$\mathbf{K_{i,t}} = \frac{\mathbf{KL_{i,t}}}{\boldsymbol{\lambda}\mathbf{F3_i}} * \left(\frac{\boldsymbol{\gamma F3_i}}{(\mathbf{1}+\boldsymbol{tk_i}) * \boldsymbol{PK_t}}\right)^{\boldsymbol{\sigma F3_i}} * \left[\left(\boldsymbol{\gamma F3_i^{\sigma F3_i}} * \left((\mathbf{1}+\boldsymbol{tk_i}) * \boldsymbol{PK_t}\right)^{(\mathbf{1}-\boldsymbol{\sigma F3_i})}\right) + \left((\mathbf{1}-\boldsymbol{\gamma F3_i})^{\boldsymbol{\sigma F3_i}} * \left((\mathbf{1}+\boldsymbol{tl_i}) * \boldsymbol{PL_t}\right)^{(\mathbf{1}-\boldsymbol{\sigma F3_i})}\right)\right]^{\left(\frac{\boldsymbol{\sigma F2_i}}{(\mathbf{1}-\boldsymbol{\sigma F2_i})}\right)}$	EQ 1.7	Firms' demand for capital (3rd nest)
$\mathbf{L_{i,t}} = \frac{\mathbf{KL_{i,t}}}{\boldsymbol{\lambda}\mathbf{F3_i}} * \left(\frac{(\mathbf{1}-\boldsymbol{\gamma F3_i})}{(\mathbf{1}+\boldsymbol{tl_i}) * \boldsymbol{PL_t}}\right)^{\boldsymbol{\sigma F3}} * \left[\left(\boldsymbol{\gamma F3_i^{\sigma F3_i}} * \left((\mathbf{1}+\boldsymbol{tk_i}) * \boldsymbol{PK_t}\right)^{(\mathbf{1}-\boldsymbol{\sigma F3_i})}\right) + \left((\mathbf{1}-\boldsymbol{\gamma F3_i})^{\boldsymbol{\sigma F3_i}} * \left((\mathbf{1}+\boldsymbol{tl_i}) * \boldsymbol{PL_t}\right)^{(\mathbf{1}-\boldsymbol{\sigma F3_i})}\right)\right]^{\left(\frac{\boldsymbol{\sigma F2_i}}{(\mathbf{1}-\boldsymbol{\sigma F2_i})}\right)}$	EQ 1.8	Firms' demand for labour (3rd nest)
$\boldsymbol{PKL_{i,t}} * \boldsymbol{KL_{i,t}} = \left((\mathbf{1}+\boldsymbol{tk_i}) * \boldsymbol{PK_t} * \boldsymbol{K_{i,t}}\right) + \left((\mathbf{1}+\boldsymbol{tl_i}) * \boldsymbol{PL_t} * \boldsymbol{L_{i,t}}\right)$	EQ 1.9	Firms' zero profit condition (3rd nest)
Household block		
$\boldsymbol{Y_t} = \boldsymbol{PK_t} * \boldsymbol{KS_t} + \boldsymbol{PL_t} * (\boldsymbol{LS_t} - \boldsymbol{UNEMP_t}) + \boldsymbol{TSS_t} * \boldsymbol{PTS_t} + \boldsymbol{THS_t} * \boldsymbol{PTH_t} + \boldsymbol{TRF_t}$	EQ 2.1	Household's income
$\boldsymbol{SH_t} = \boldsymbol{mps} * (\boldsymbol{Y_t} - \boldsymbol{ty} * \boldsymbol{Y_t})$	EQ 2.2	Household's saving
$\boldsymbol{CBUD_t} = (\mathbf{1}-\boldsymbol{ty}) * \boldsymbol{Y_t} - \boldsymbol{SH_t}$	EQ 2.3	Household's consumption expenditure
$(\mathbf{1}+\boldsymbol{tc_i}) * \boldsymbol{P_{i,t}} * \boldsymbol{C_{i,t}} = (\mathbf{1}+\boldsymbol{tc_i}) * \boldsymbol{P_{i,t}} * \boldsymbol{\mu H_i} + \boldsymbol{\alpha HLES_i} * (\boldsymbol{CBUD_t} - \sum_j (\boldsymbol{\mu H_j} * (\mathbf{1}+\boldsymbol{tc_j}) * \boldsymbol{P_{j,t}})$	EQ 2.4	Households' demand for commodities
$\left(\frac{\left(\frac{\boldsymbol{PL_t}}{\boldsymbol{PCINDEX_t}}\right)}{\left(\frac{\boldsymbol{PL_0}}{\boldsymbol{PCINDEX_0}}\right)}\right) = \boldsymbol{\varphi} * \left(\frac{\frac{\boldsymbol{UNEMP_t}}{\boldsymbol{LS_t}}}{\frac{\boldsymbol{UNEMP_0}}{\boldsymbol{LS_0}}} - \mathbf{1}\right)$	EQ 2.5	Philips wage curve
$\boldsymbol{PCINDEX_t} = \frac{\left(\sum_i \left((\mathbf{1}+\boldsymbol{tc_i}) * \boldsymbol{P_{i,t}} * \boldsymbol{C_{i,0}}\right)\right)}{\left(\sum_i \left((\mathbf{1}+\boldsymbol{tc_i}) * \boldsymbol{P_{i,0}} * \boldsymbol{C_{i,0}}\right)\right)}$	EQ 2.6	Consumer price index

Saving and investment block		
$S_t = SH_t + PCINDEX_t * SG_t + SF_t * ER_t$	EQ 3.1	Total savings
$P_{i,t} * I_{i,t} = \alpha I_i * S_t$	EQ 3.2	Demand for investment
Government block		
$P_{i,t} * CG_i = \alpha CG_i * (TAXR_t - TRF_t - SG_t * PCINDEX_t)$	EQ 4.1	Government's demand for consumption
$PK_t * KG_t = \alpha KG * (TAXR_t - TRF_t - SG_t * PCINDEX_t)$	EQ 4.2	Government's demand for capital
$PL_t * LG_t = \alpha LG * (TAXR_t - TRF_t - SG_t * PCINDEX_t)$	EQ 4.3	Government's demand for labour
$TAXR_t = ty * Y_t + \sum_i ((P_{i,t} * tc_i * C_{i,t}) + (PK_t * tk_i * K_{i,t}) + (PL_t * tl_i * L_{i,t}) + (tm_i * M_{i,t} * PWM_{i,t} * ER_t))$	EQ 4.4	Government's revenue (total taxes)
$TRF_t = trep * PL_t * UNEMP_t + TRO_t * PCINDEX_t$	EQ 4.5	Total transfers from the government to the household
International trade		
$E_{i,t} = \frac{XD_{i,t}}{\lambda T_i} * \left(\frac{\gamma T_i}{PE_{i,t}}\right)^{\sigma T_i} * \left((\gamma T_i^{\sigma T_i}) * \left(PE_{i,t}^{(1-\sigma T_i)}\right) + \left((1 - \gamma T_i)^{\sigma T_i} * \left(PDD_{i,t}^{(1-\sigma T_i)}\right)\right)\right)^{\frac{\sigma T_i}{1-\sigma T_i}}$	EQ 5.1	CET function for selling output to the international market
$XDD_{i,t} = \frac{XD_{i,t}}{\lambda T_i} * \left(\frac{(1 - \gamma T_i)}{PDD_i, t}\right)^{\sigma T_i} * \left((\gamma T_i^{\sigma T_i}) * \left(PE_{i,t}^{(1-\sigma T_i)}\right) + \left((1 - \gamma T_i)^{\sigma T_i} * \left(PDD_{i,t}^{(1-\sigma T_i)}\right)\right)\right)^{\frac{\sigma T_i}{1-\sigma T_i}}$	EQ 5.2	CET function for selling output to the domestic market
$PD_{i,t} * XD_{i,t} = PE_i * E_{i,t} + PDD_{i,t} * XDD_{i,t}$	EQ 5.3	Zero profit condition for the CET function

$M_{i,t} = \frac{X_{i,t}}{\lambda A_i} * \left(\frac{\gamma A_i}{PM_{i,t}}\right)^{\sigma A_i} * \left(\left(\left(\gamma A_i^{\sigma A_i}\right) * \left(PM_{i,t}^{(1-\sigma A_i)}\right)\right) + \left((1-\gamma A_i)^{\sigma A_i} * \left(PDD_{i,t}^{(1-sigmaA_i)}\right)\right)\right)^{\frac{\sigma A_i}{1-\sigma A_i}}$	EQ 5.4	Armington function for demand of imports into the domestic economy
$XDD_{i,t} = \frac{X_{i,t}}{\lambda A_i} * \left(\frac{(1-\gamma A_i)}{PDD_{i,t}}\right)^{\sigma A_i} * \left(\left(\left(\gamma A_i^{\sigma A_i}\right) * \left(PM_{i,t}^{(1-\sigma A_i)}\right)\right) + \left((1-\gamma A_i)^{\sigma A_i} * \left(PDD_{i,t}^{(1-sigmaA_i)}\right)\right)\right)^{\frac{\sigma A_i}{1-\sigma A_i}}$	EQ 5.5	Armington function for demand of locally produced goods within the local economy
$P_{i,t} * X_{i,t} = PM_{i,t} * M_{i,t} + PDD_{i,t} * XDD_{i,t}$	EQ 5.6	Zero profit condition for the Armington function
$PM_{i,t} = (1 + tm_i) * ER_t * PWM_{i,0}$	EQ 5.7	Price of imports
$PE_{i,t} = ER_t * PWE_{i,t}$	EQ 5.8	Price of exports
$\sum_i (M_{i,t} * PWM_{i,0}) = \sum_i (PWE_{i,0} * E_{i,t}) + SF_t$	EQ 5.9	Zero profit condition for international trade
Market clearing		
$X_{i,t} = C_{i,t} + I_{i,t} + CG_{i,t} \sum_j (io_{i,j,t} * XD_{j,t})$	EQ 6.1	Market clearing for output
$TSS_{i,t} = \sum_i TS_{i,t}$	EQ 6.2	Market clearing for softwood stumpage
$THS_{i,t} = \sum_i TH_{i,t}$	EQ 6.3	Market clearing for hardwood stumpage
$KS_{i,t} = KG_t + \sum_i K_{i,t}$	EQ 6.4	Market clearing for capital
$LS_{i,t} = LG_t - UNEMP_t + \sum_i L_{i,t}$	EQ 6.5	Market clearing for labour
Market closures		

$\overline{LS_t} = LS_t$	EQ 7.1	Exogenously fix labour supply
$\overline{KS_t} = KS_t$	EQ 7.2	Exogenously fix capitula supply
$\overline{TSS_t} = TSS_t$	EQ 7.3	Exogenously fix softwood stumpage supply
$\overline{THS_t} = THS_t$	EQ 7.4	Exogenously fix hardwood stumpage supply
$\overline{SG_0} = SG_t$	EQ 7.5	Exogenously fix government saving
$\overline{SF_0} = SF_t$	EQ 7.6	Exogenously fix government saving
$\overline{PL_0} = PL_t$	EQ 7.7	Fix price of labour (wages) for the numeraire
Dynamic growth pathways		
$\overline{LS_t} = LS_{t-1} * (1 + GRL_t)$	EQ 8.1	Exogenously fixing the labour supply growth path
$RRR_t = \frac{S_t * \psi}{PK_t * KS_t}$	EQ 8.2	Real rate of return
$\overline{KS_t} = KS_{t-1} * (1 + RRR_t)$	EQ 8.3	Exogenously fixing the capital supply growth path
$\overline{TSS_t} = TSS_{t-1} * (1 + \mathrm{GRSS_t})$	EQ 8.4	Exogenously fixing the softwood stumpage supply growth path
$\overline{THS_t} = THS_{t-1} * (1 + GRHS_t))$	EQ 8.5	Exogenously fixing the hardwood stumpage supply growth path

Chapter 4 General conclusion

4.1 General outcomes of this thesis

This thesis has developed an enhanced economic and ecological modeling framework to assess the economic impacts of climate change in forests, implemented the framework in the case-study regions of New Brunswick and Quebec, and considered the interactions between climate change and timber harvesting rates and how they impact stand/forest dynamics, wood supplies and the economy. It contributes to the current literature by: (i) developing an enhanced CGE model that incorporates hardwood and softwood supply inputs, along with hardwood and softwood logging & forestry sectors; and (ii) joining the enhanced CGE model with a forest-landscape (PICUS-LANDIS II) modeling framework. This process resulted in the creation of the PICUS-LANDIS-CGE framework. The PICUS-LANDIS-CGE framework provides more robust economic estimators when compared to a stand-alone CGE model. The thesis has demonstrated the robustness and application of the PICUS-LANDIS-CGE framework by applying it to the case study regions of New Brunswick (Chapter 2) and Québec (Chapter 3).

Chapter 2 established the enhanced CGE model along with the methodology used to disaggregate the forestry and logging sector into a hardwood forestry and logging sector (H-FOR) and a softwood forestry and logging sector (S-FOR). Furthermore, chapter 2 presents the PICUS-LANDIS-CGE framework and demonstrates its application by examining the economic impact caused by climate change altering the structure and composition of New Brunswick's forests, in both the short and long

term. Lastly, the chapter highlights the robustness of the PICUS-LANDIS-CGE framework by comparing the economic estimators to other forestry related CGE studies.

Chapter 3 builds on the previous chapter by applying the PICUS-LANDIS-CGE framework to Québec and examining climate change and harvesting rate interactions. This chapter contributes to the current literature by providing a unique perspective on the economic and ecological trade-offs associated with changing harvesting rates to influence the resilience of the forest to climate change.

4.2 Summary of important findings

4.2.1 Biomass harvested and wood supply

From an ecological perspective, this thesis has shown that climate change will negatively impact the abundance of cold-adapted tree species (e.g., balsam fir, white, black, and red spruces) within the case study regions. This impact translates to a reduction in biomass harvested from individual softwood species, as well as a reduction in the regional supply of softwood. Meanwhile, warm-adapted hardwood species experience a minor increase in forest abundance, and volume of biomass harvested, under mild climate change (RCP 2.6 and RCP 4.5). However, this increase was not sustained under RCP 8.5. Furthermore, the increase in above-ground biomass, volume of biomass harvested of individual species, and hardwood supply was not proportional to the decrease in above-ground biomass, volume of biomass harvested of individual species, and softwood supply. As such climate change results in a decrease in total forest abundances, as well as volume harvested, and aggerated supply of wood.

In both case study regions climate change did begin to have a significant impact on biomass harvested until 2050; however, after this point it becomes the main driver of change within the forest landscape.

4.2.2 Sectorial impacts

Forestry and wood-related sectors are the most sensitive to a change in the quantity and composition of the regional wood supply. In both case study regions, climate change typically had a negative impact on the value of output, with the largest negative impact occurring under RCP 8.5. Interestingly, H-FOR did not experience an increase in output value even under scenarios that saw an increase in hardwood supply. This was shown to be the result of output from S-FOR acting as a limiting factor of production in these scenarios.

Wood-related manufacturing sectors were also negatively impacted by climate change altering the quantity and composition of the regional wood supply. This is due to these sectors' reliance on intermediate input from both H-FOR and S-FOR. However, due to these sectors demanding a greater amount of intermediate input from S-FOR compared to H-FOR outputs, they were more sensitive to a change in the supply of softwood, compared to hardwood.

4.2.3 Macro-economic impacts

From a macro-economic perspective, the economic impacts of climate change on the case-study regions' forests is relativity small when compared to the ecological

and sectorial impacts. The small impact on macro-economic variables (e.g., gross domestic product, household income) across both case study regions is likely due to the relatively small size of the forestry and wood-related sectors, compared to other sectors and industries within each province by 2150.

4.2.4 Climate change and harvesting interactions

In Chapter 3, harvesting rates were shown to affect the intensity with which climate change impacts Quebec's forests. Specifically, reducing the annual allowable cut (AAC) decreases the severity of climate change impacts. Likewise, increasing the AAC results in an increase in the severity of climate change impacts. However, harvesting rate changes were found to dominate climate change in affecting the AAC, forest sector output, and the greater economy.

4.3 Limitations

Although the thesis provides a unique insight into how climate change will induce a change in forest structure and composition, thereby impacting regional economies, it is important to acknowledge possible limitations both of individual chapters and of the study as whole. Limitations of the individual chapters have been addressed within each chapter, however, there are a few limitations that stretch the entirety of the thesis. The following will highlight several of these limitations.

First, the thesis uses a single regional CGE model. Although such models are robust, they do not account for changes outside of the study region. As such the single

regional CGE model has the potential to over or underestimate the impact of climate change altering forest structure and composition, as it is unable to model the global impact of climate change altering forest structure and composition. This is highlighted by study regions being able to import additional forestry and wood-related goods into the economy under climate change. In reality, this may not be feasible because if climate change is severe enough to impact the supply of hardwood and softwood within the case study regions it will also be severe enough to impact the global wood supply (Kirilenko & Sedjo, 2007). Hence, if the decrease in regional wood supply is greater than the decrease in global wood supply, then the single regional CGE model may underestimate the impact of climate change altering the structure and composition of the forest. In this situation the case study region may still be able to import additional forestry and wood-related goods into the economy from the Rest of the World (RoW). However, the price of these imports would be significantly higher than what is shown within the single region CGE model. Meanwhile, if the decrease in regional wood supply is less than the decrease in global wood supply the impacts maybe over overestimated, as the global reduction in the supply of forestry and wood-related goods would cause a significant increase in export prices of these goods. Domestic producers of forestry and wood-related goods would be able to take advantage of the increase in export price by exporting additional goods.

Second, modifications were made to the production block of the CGE model to disaggregate wood supply into hardwood and softwood supplies. However, the first nest remained unchanged and thus uses a fixed share Leontief production function to

determine the demand for intermediate goods. Although the use of the fixed share Leontief production function is widely accepted (Lantz et al., 2022; Liu et al., 2019; Ochuodho et al., 2016; Sharma et al., 2022; Withey et al., 2021), it may not be the best representation of how sectors view and respond to changes outputs from H-FOR and S-FOR. This is because the fixed share Leontief production function makes two assumptions. First, firms have determined their optimal combination of intermediate goods, which is displayed within the SAM. Second, all sectors produce a unique good, which results in limited substitution between intermediate goods. These assumptions hold for the majority of the sectors within the economy, with possible expectations being H-FOR and S-FOR. Specifically, as although hardwood and softwood have different characteristics, these differences are likely only notable by wood related sectors that rely on the differences in characterises to produces their unique good (e.g., pulpwood, sawlogs, paper, etc.). Meanwhile, non-wood related sectors (e.g., education and healthcare) may not be as reliant on the individual characteristics of hardwood and softwood to producer their good, and as such would likely be willing to substitute between hardwood and softwood with a preference for the cheapest option. In this scenario, using a fixed share Leontief production function may not provide the most accurate representation, of the production function of these sectors would view the output from H-FOR and S-FOR to be non-unique.

Third, although the elasticities in the CGE model are calibrated using the most up-to-date peer-reviewed literature, they may not represent the exact preferences of agents within each case study region. This is the result of the literature in some cases

providing such elasticities at the national level, and thereby not accounting for any differences between provinces. This limitation is a reoccurring problem of CGE studies and has been described in depth in Ochuodho (2013). To remove some of the uncertainty of this limitation, this thesis employed a sensitivity analysis as part of Chapter 2.

Lastly, the temporal scope of thesis (2015-2150) is quite large especially for an economic study. As such there is a degree of uncertainty in regards to both the ecological and economic results that occur in the later half of the temporal scope. The uncertainty stems from the multiple different pathways that could occur under the same climate scenario. This is due to how both natural disturbances (i.e., probabilistic event) and harvesting selection (i.e., random evet) are simulated within the framework. To try and account for this uncertainty PICUS-LANDIS is run multiple times each climate and harvesting scenario. Furthermore, it is also likely that the economic elasticities used within this thesis will change in future years as culture normal and technology continue to evolve. This uncertainty regarding future elasticises persist in most long-term CGE studies, although it maybe able to be address by running the CGE model multiple times using different steady-state growth rates.

4.4 Future research

The establishment of the methodology created within this thesis along with the findings provides multiple directions for future research. Possible directions include incorporating other forms of natural capital, accounting for non-market goods, as well

as establishing a more rigorous coupling process between the CGE model and the forest landscape model.

Regarding natural capital, it is clear that forests are not the only form of natural capital that will be impacted by climate change. Studies have shown that farmland, fish stocks, game stocks, as well as oil, gas, and mineral extraction will all be negatively impacted by climate change and environmental policies (Allison et al., 2009; Fezzi & Bateman, 2015). These impacts may have important interaction effects with the forest sector. Incorporating other forms of natural capital into future CGE models will provide a better understanding of the economic impact of climate change.

While there are studies that use CGE models to examine the impact of climate change on other forms of natural capital (Ochuodho et al., 2016; Pan et al., 2022; Withey et al., 2016), these studies typically rely on peer-reviewed papers and expert opinions to determine the impact of climate change. Hence, it would be beneficial to join a CGE model with multiple discipline-specific ecological models. In doing so each discipline-specific model would be responsible for stimulating the change in natural capital under various climate scenarios, while the CGE model simulates the cumulative impact the changes will have on the economy. This framework would be especially beneficial for Atlantic Canada, as the region has a high dependency on agriculture, forests, and fisheries (wild-caught, and farmed).

Future CGE studies should also consider the economic impact that climate change has on non-market goods and services. Currently, CGE studies typically focus on

the impact climate change will have on market goods and services (e.g., wood products). They don't tend to consider the impact climate change will have on non-market goods and services, which can include several indirect-use or non-use ecosystem services (e.g., carbon sequestration, intrinsic value, biodiversity). There is currently a push to incorporate Systems of Environmental and Economic Accounts (SEEA) into CGE models (Ochuodho & Alavalapati, 2016), which allows the SAM to be extended to account for various non-market goods. This framework has recently been used in conjunction with a dynamic land-use model to simulate the economic and ecological impact of various policies (Banerjee et al., 2020). Incorporating market and non-market goods into a CGE model allows for a more accurate simulation of the impacts associated with climate change altering natural capital.

Accounting for natural capital impacts of climate change would be especially beneficial for the discipline of forest economics, as forest carbon sequestration is increasingly becoming a valuable aspect of forestry, with some policymakers and researchers suggesting that forest management practices that optimize carbon sequestration are a valuable tool in limiting CO_2 (Hennigar et al., 2008; Liu & Wu, 2017). Furthermore, recent studies have used PICUS-LANDIS to examine the extent to which climate change will impact such non-market forest services as wildlife habitat (St-Laurent et al., 2022; Tremblay et al., 2018) and carbon sequestration (Moreau et al., 2022). These studies typically show that climate change will have a negative impact on non-market forest services; however, enhanced forest management may reduce these impacts. These studies do not conduct a formal economic analysis. As such it is

unknown if the monetary benefit provided by these non-market forest services is comparable to the economic loss caused by enhanced forest management.

Incorporating CO_2 emissions and sequestration into the current PICUS-LANDIS-CGE framework would also allow for a contribution to the net zero literature (Harris et al., 2021; Strengers et al., 2008). In doing so the framework would be able to examine the effectiveness of using both forest management and economic policies (e.g., carbon tax) to lower CO_2 emissions.

Lastly, the establishment of the PICUS-LANDIS-CGE framework highlights the need for a more integrated approach that can better represent the interaction between the economy and the biophysical world. Currently, in the PICUS-LANDIS-CGE framework, all three models are run completely separate of each other, with PICUS being run first, followed by LANDIS, and lastly the CGE model. Although this process provides a robust understanding of how changes in the forest landscape will impact the economy, it is not fully integrated into one software system. Additionally, the framework currently cannot analyze the impact that a changing economy will have on the forest landscape. Therefore, creating a fully integrated software system in which the models are run in steps would provide greater insight into the ecological impacts caused by changes in the economy. This framework in conjunction with incorporating non-market goods into the CGE models would provide a unique insight into the economic policies required to preserve both market and non-market forest services under climate change. It is my intent to conduct further research along this line of inquiry in future research.

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Vita

Candidate's full name:

Galen Robert James McMonagle

Universities attended (with dates and degree obtained)

2019-current MSc. Environmental Management. Candidate, University of New Brunswick

2019 BSc. Environmental Science and Economics, Dalhousie University.

Publication:

Lantz, V., **McMonagle, G**., Hennigar, C., Sharma, C., Withey, P., & Ochuodho, T. (2022). Forest Succession, Management and the Economy Under a Changing Climate: Coupling Economic and Forest Management Models to Assess Impacts and Adaptation Options. *Forest Policy and Economics*, *142*(September), 102781. https://doi.org/10.2139/ssrn.4039425

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