Forest succession, plantations and the economy under a changing climate: coupling Woodstock and CGE models to assess impacts and adaptation options in New Brunswick, Canada

Report prepared by:
Van Lantz[a], Galen McMonagle[a], Chris Hennigar[a], Chinmay Sharma[a], Patrick Withey[b], Thomas Ochuodho[c]

March 15, 2021

Funding provided by:
Natural Resource Canada's Climate Change Adaptation Program

[a] Faculty of Forestry and Environmental Management. University of New Brunswick, Fredericton, New Brunswick.
[b] Department of Economics. St Francis Xavier University. Antigonish, Nova Scotia.
[c] Department of Forestry and Natural Resources, University of Kentucky, Lexington, Kentucky.

Abstract

Climate change is expected to have significant impacts on forests through increases in temperature, which affects successional dynamics of tree species, and drought regimes, causing plantations to fail. Research is needed to better understand how these factors will affect forests and economies in different regions, and how we can best adapt. To shed some light on these issues, we couple a forest management model (Woodstock) with an economic model (Computable General Equilibrium) to analyze the potential climate change impacts and adaptation options on timber supply and the economy over the 2015-95 period in the case-study province of New Brunswick, Canada. We estimate that climate change will have relatively large negative impacts on softwood timber supply (at 26% by 2095), softwood forestry & logging sector output quantity (at 12% by 2095), and softwood-dependent forestry manufacturing sector output (ranging from 6% to 27% by 2095). Negative impacts on GDP will be relatively smaller (at up to a 0.35% reduction by 2095). Adapting to these climate-related changes by planting drought-resistant softwood seedlings or hardwood seedlings in place of failed softwood plantations can minimize these negative impacts, and in the latter case, positively impact hardwood timber supply (up to a 30% by 2095), hardwood forestry & logging sector output quantity (at 2.3% by 2095), and hardwood-dependent forestry manufacturing sector output (ranging from 0.2% to 2.5% by 2095). While the former adaptation option is supported using cost-benefit analysis, the latter is not – due to the large incremental costs of growing, planting, and tending hardwood seedlings. Methods developed in this study can be applied in other regions to help guide decision-making around forest management in the face of a changing climate.

1. Introduction

The forests of New Brunswick have provided its citizens with a source of subsistence and economic growth for many centuries. Today, the forest sector harvests just over 6 million m3 of softwood and 3 million m3 of hardwood volume annually (CCFM 2020), and contributes $1.3 billion, or 4.3%, to provincial GDP (NRCan 2020). The industry also directly employs approximately 10,000 individuals within the Province (NRCan 2020).

The relatively heavy dependence that the New Brunswick forest sector has on the province's forests for its supply of timber leaves it highly susceptible to natural and man-made disturbances such as climate change. Indeed, New Brunswick's (and Canada's) forests are already experiencing the effects of climate change. Some of the most visible effects include changes in the frequency and severity of droughts, severe winds, and damaging insect and disease attacks (Williamson et al. 2009). Other, longer term effects include changes in forest growth and succession, among others (Taylor et al. 2017). As these effects are largely expected to intensify over the next few decades, there is increasing attention being paid to the potential impacts this will have on the forest sector and the need to adapt (Lemprière et al. 2008; Taylor et al. 2017).

A number of studies have examined the biophysical and economics of climate change in Canadian and/or North American forests using a variety of methods. For instance, some studies link climate change scenarios with ecological models to estimate forest productivity changes over time, and then link these with global timber market models to assess impacts on timber production, costs, and revenues in global and country-level forest sectors (for instance, see Sohngen et al. 2005, 2001; Perez-Garcia et al. 2002, 1997). Findings in these studies often reveal significant timber production and economic losses for Canadian timber producers under the various climate change scenarios. For instance, Perez-Garcia et al. (2002) estimate that Canadian timber production may decrease by as much as 4% from 2000 to 2040, and that economic losses to Canadian producers may be among the highest of all producing regions.

A few additional studies have estimated economy-wide impacts of climate change and adaptation using computable general equilibrium (CGE) models (see Williamson et al. 2008; Ochuodho et al. 2012, 2016; Ochuodho & Lantz, 2014; Boccanfuso et al. 2017).[1] For instance, Williamson et al. (2008) link climate change scenarios with an ecological model to estimate forest productivity changes over time, and then link these with a CGE model to assess the economic impacts that climate change will have on a forest-dependent community in British Columbia. They find that climate change is expected to increase forest productivity and household income in the region by as much as 5%. Ochuodho et al. (2012), on the other hand, use estimates of forest productivity, pest, and fire changes from the literature to assess the potential economic impacts costs, and benefits of climate change and adaptation on Canadian provincial forests. They find a wide range of positive and negative timber production and economic impact possibilities, depending on the scenario considered. They emphasize the need to directly model the timber production impacts of climate change and adaptation using a forest management model calibrated to a specific region and use the resulting timber supply

[1] Other economic analysis of climate change impacts on Canadian and/or North American forests include Nordhaus (1991), Mendelsohn et al. (2000), Kemfert (2002), Hope (2006) and a host of others who use integrated assessment and CGE models of the world economies. However, since these studies incorporate the effects of climate change on many sectors at once (e.g., forest, agriculture, energy, human health, etc.), and as such the contribution of forest-related impacts is not identified.

output in a CGE model to assess economic outcomes. The objective of this study is to undertake this analysis.

In this study we analyze the potential climate change impacts and adaptation on New Brunswick’s timber supply and economy by coupling a forest management model with a CGE model. We focus our analysis on the effect that climate change will have on forest succession, as this has been deemed one of the most significant (and measurable) climate-induced changes predicted to occur in New Brunswick’s forests over the long term (see Taylor et al. 2017). More specifically, as the climate warms, several tree species (e.g., spruce and fir) are expected to no longer naturally regenerate after harvest, while several others (e.g., tolerant hardwood and red maple) are expected to exhibit enhanced regeneration. Furthermore, increased occurrence and severity of drought is expected to result in a possible failure of planted softwood stock to regenerate (Vaughan et al. 2021; Fisichelli et al. 2014; D’Orangeville et al. 2013). Within this context, we consider 4 scenarios, based on different assumptions regarding the timing of failure for planted softwood stock to regenerate, and the options to adapt by either planting genetically modified softwood stock, or planting hardwood stock on harvested softwood plantation areas.

Each climate change and adaptation scenario is fed into a Woodstock forest management model (Remsoft 1997) to produce softwood and hardwood timber production estimates from 2020-2095. The timber production estimates are then scaled-up to the provincial level, converted into softwood and hardwood stumpage values, and used as inputs into a single region, recursive dynamic CGE model, calibrated to the New Brunswick economy.

For each scenario, we present the dynamic impacts on a series of forest-level indicators (e.g., tree species volume harvested, aggregated softwood and hardwood volume harvested) and economic indicators (e.g., sector output values; prices; household consumption; government expenditures; export and import values; labour, capital, and stumpage value expenditures; GDP). We also conduct a preliminary cost-benefit analysis of selected adaptation options associated with modified planting regimes.

This research is important as it builds on previous studies investigating the biophysical and economic impacts of climate change in forests. To our knowledge, this is the first study to assess the economics of climate change by coupling a forest management model with a CGE model. Previous analysis has either used ecological models or relied on literature in other regions to infer timber supply impacts and use them in CGE models. Furthermore, while previous CGE model analyses have focused on examining the effects of aggregated timber supply changes on the economy, our analysis will better account for individual softwood vs. hardwood timber supply changes by disaggregating the logging sector into softwood and hardwood sub-sectors. These methodological advances will be helpful in creating more accurate economic impact estimates, and also provide the basis to better inform future forest management plans that aim to mitigate the damage caused by climate change.

The remainder of this article is organized as follows. Section 2 describes the methods used to model the timber supply and economics impacts of climate change and adaptation. Section 3 provides the results of the analysis. Finally, Section 4 presents a discussion of the findings, outlines some of the limitations, and concludes the study.

2. Methods

Forest management modeling:

To assess the impacts of climate change on New Brunswick's forests, we update and extend a New Brunswick Department of Energy and Resource Development (NBERD) Crown land forest management model, which uses Remsoft Inc.'s Woodstock forest management software.[2] Within the software, forest features such as initial stand types, age class distributions, areas, stand yields, natural transition patterns, disturbance transition patterns, and possible forest interventions (e.g., clearcutting, partial-cutting, commercial thinning, planting and pre-commercial thinning) are represented for each Crown license.. In our analysis, an 80-year planning horizon is defined and time periods are specified by 5-year intervals, beginning in 2020. Additionally, seven tree species supply groupings are defined including spruce-pine-fir (SPF) (*Picea mariana, Picea rubens, Picea glauca, Pinus banksiana and Abies balsamea*), pine (Pi) (*Pinus strobus and Pinus resinosa*), cedar (*Thuja occidentalis*), hemlock (*Tsuga canadensis*), tolerant hardwood (TH) (*Acer saccharrum, Betula allegheniensis*, *Fagus grandifolia*), intolerant hardwood (IH) (*Populus tremuloides, Acer rubrum, and Betula papyrifera),* and larch (*Larix laricina*) (Tl).

Once an objective function and constraints are defined in the model, the model files are served into the linear programming optimization software MOSEK (2004). Woodstock takes the solution provided by MOSEK and presents the forest indicator results in user-defined report files. In our analysis, we employ a typical objective function of maximizing total volume of

[2] Woodstock is used worldwide for strategic forest planning and management (Walters 1993). Recent academic studies that use of the software in the context of climate change and adaptation include: Dymond et al. (2020), Lundholm (2020; 2019), and Dhital et al. (2015).

merchantable timber harvested over the 75-year planning horizon with a 5% discount rate to value harvest today higher than harvest later in the planning horizon. Harvesting constraints include: non-declining harvest constraint under baseline (no climate change) conditions, upper bounds on silviculture amounts tied to provincial silviculture budget constraints, non-declining operable growing stock after 2080, and period-to-period flow-control on area treated by treatment. Forest indicators of particular interest for the current analysis include softwood and hardwood harvest levels (m^3 per period).

Wood volume is measured in the model through stand-type volume yield curves. Yield curves were originally developed by the New Brunswick Department of Energy and Resource Development's Growth and Yield Unit using the Open Stand Model – Acadian Variant (www.forusresearch.com) to produce 5-year period forecasts of merchantable volume of wood by each stand type and species product group. Forest succession dynamics in the model are based on New Brunswick historical regeneration observations from 1990s-2000s FDS (pre-cut) timber surveys and photo-interpreted post-cut succession response (proportion of species composition types; aka FUNA types).

To account for future climate change effects on forest succession, a GBM (gradient boosted machine ensemble classification trees) model was used to predict the multinomial distribution of regenerating FUNA types as a function of: (i) climate variables (mean annual temp, DJF mean temp); (ii) disturbance type (clearcut, overstory removal); and (iii) pre-cut FUNA type (from timber cruise).

It should be noted here that, under the IPCC's climate change condition RCP 8.5 temperature (even in the highlands) will exceed that of southern New Brunswick by 2080, so the GMB model is very limited by New Brunswick's geographic climate range and cannot be confidently used for southern New Brunswick beyond 2035 and northern New Brunswick beyond 2050. Therefore, we consulted Natural Resource Canada's tree species climate-suitability maps (planthardiness.gc.ca; MaxEnt; composite-AR5; RCP8.5) for periods 2040-2070 and 2070-2010 for all commercial tree species in New Brunswick to roughly estimate relative reductions in suitability from today to 2100 for: (i) southern ecoregions 5, 6 and 7; northern ecoregions 2 and 3; and (iii) highlands/Fundy coast ecoregions 1 and 4, where suitability was assumed to relate to probability of successful natural regeneration.

Where species were not expected to successfully regenerate/compete using the climate-suitability maps, a zero multiplier was used in the yield curve indicating these species would no longer regenerate naturally. By setting these unsuitable FUNA to zero, remaining proportions of suitable FUNA were proportionally increased to sum to 100%. Remaining FUNA will still contain trace to low amounts of other non-suitable species, but the dominant species regenerating will largely shift toward more suitable species using the succession matrix.

Economic modeling:

CGE models are a class of economic impact models that use economic data to estimate how an economy might react to changes in policies, markets, technologies or other such factors. CGE modeling has become a popular tool for analyzing economic and welfare impacts of policy options in natural resources management. Researchers have applied this technique to examine a wide range of forest-related policies and natural/human disturbances such as land-use changes (Zhang et al. 2005), pest outbreaks (Liu et al. 2019; Corbett et al. 2016; Chang et al.

2012), environmental regulations (Das et al. 2005), deforestation (Banerjee and Alavalapati 2009), and climate change, as previously described.

We develop a single-region, recursive dynamic CGE model for the New Brunswick economy. The model is based on the neoclassical modeling tradition originally developed by Dervis et al. (1982). The basic specification is similar to that used in some of our previous work (e.g., Liu et al. 2019; Corbett et al. 2016) but is augmented in two ways: (i) we break out several forest manufacturing sectors from the aggregated manufacturing sector (as a result of Statistics Canada now providing this level of detail); and (ii) we break out softwood and hardwood logging sectors from the aggregated logging sector. This latter augmentation was required to match-up with the different effects that climate change will have on softwood vs hardwood tree species. Appendix II provides a detailed description of the model.

The model is formulated as a set of simultaneous linear and non-linear equations, consisting of a production block, a household block, a government block, and a trade block. Market clearing conditions guarantee that supply and demand are equated for commodities and factors of production in each sector.

In the production block, New Brunswick is assumed to be a small open economy consisting of 27 sectors (see Table 1), 8 of which represent the forest sector directly (i.e., S-FOR, H-FOR, SAW-MANUF, VEN-MANUF, OW-MANUF, PULP-MANUF, CP-MANUF, and PR-MANUF). Supply equals demand for all commodities. Demand for each commodity in each sector is based on intermediate inputs demanded from related sectors, final demand by consumers, government and investment, and exports. Supply of commodities in each sector comes from imports and domestic production, which includes intermediate inputs supplied by other sectors and value-added production in each sector based on factors of production. The factors of production include labour, capital, and stumpage value (the latter of which is only used in the softwood and hardwood logging sectors). Labour and capital are assumed to be mobile across sectors.

Table 1: Production sectors included in the CGE model

sec1	Crop and animal production (CROP)	sec15	Other manufacturing (O-MANUF)
sec2	Softwood Forestry & logging (S-FOR)	sec16	Wholesale Trade (WT)
sec3	Hardwood Forestry & logging (H-FOR)	sec17	Retail trade (RT)
sec4	Fishing, hunting and trapping (FISH)	sec18	Transportation & warehousing (TRANSP)
sec5	Support activities for agric/for (SUPP)	sec19	Information & cultural industries (INFO)
sec6	Mining, oil, and gas extraction (MIN)	sec20	Finance, insurance, real estate (FIN)
sec7	Utilities (UTIL)	sec21	Professional, scientific, tech services (PROF)
sec8	Construction (CONST)	sec22	Admin support, waste mngt, etc. (ADMIN)
sec9	Sawmills & wood preservation (SAW-MANUF)	sec23	Education services (EDU)
sec10	Veneer plywood & eng wood (VEN-MANUF)	sec24	Healthcare & social assistance (HEALTH)
sec11	Other wood product manuf (OW-MANUF)	sec25	Arts, entertainment, education (ARTS)
sec12	Pulp paper & cardboard mills (PULP-MANUF)	sec26	Accommodation & food services (ACC)
sec13	Converted paper product manuf (CP-MANUF)	sec27	Other services (OTHER)
sec14	Printing & support activities (PR-MANUF)		

A nested CES structure allows for a trade-off between inputs at different levels (or nests). At the top nest, a composite (or bundle) of labour, capital and stumpage value is combined with intermediate inputs using a fixed-share Leontief technology.[3] At the second level, producers who use stumpage (i.e., the hardwood and softwood forestry & logging sectors) choose between a labour-capital bundle and either a hardwood or a softwood stumpage value (these stumpage inputs are sector-specific). At the third level, producers choose between labour and capital. In nests two and three, the choice of inputs are made by minimizing the costs of production subject to a constant elasticity of substitution (CES)

[3] Fixed-shares are used for intermediates since their proportions are thought to be mostly determined by existing technology rather than producer decision-making.

production function. The price of final output in each sector is derived from the combined costs of value-added and intermediates.

In the household block, there is a representative household who supplies labour and capital to firms, and who chooses to consume commodities in order to maximize their utility (or satisfaction). Sector-specific demand for commodities is based on a Stone-Geary utility function, or more explicitly a Linear Expenditure System. Household income is based on factors of production (less unemployment) and transfers from government. Total savings is the sum of household and foreign savings. Investment demand is determined by total savings, where a Cobb-Douglas investment function is specified for each commodity. Unemployment is endogenous in the model and is determined based on a traditional Phillips curve.

In the government block, the government receives transfers through taxes such as income, consumption, input and import taxes, and spends on consumer commodities in each sector, hiring labour (public sector), investing in capital, and providing transfers to individual households. Government demand for commodities is based on a Cobb-Douglas utility function.

In the trade block, all domestic production can either go to the domestic market (as intermediate inputs, consumption, investment, government consumption) or can be exported. Likewise, inputs in the production process can either be imported (as intermediate inputs) or supplied domestically (intermediate inputs, labour, capital). A CES Armington specification is used so that domestic consumers can choose between domestic production and imported goods. Imports relative to domestic goods are determined by the relative prices of each type of good. Higher domestic prices due to shocks will cause an increase in the import-domestic demand ratio. On the supply (export) side, the domestic outputs delivered to domestic market are differentiated from products produced for export by the same sector using a constant elasticity of transformation (CET). As with imports, producers will rely on relative prices to determine whether or not goods are exported, as they seek to sell where the returns are highest, in order to maximize profit.

Finally, in the market clearing block, market clearing conditions ensure that demand and supply are equated for both commodities and factors in every sector. For factors to achieve equilibrium, factor prices in these markets must adjust to ensure that demand equals supply. However, unemployment (voluntary and involuntary) exists in the model. For commodities, final demand (consumption, investment, government consumption), exports and intermediate inputs demanded by each sector must balance with production (labour, capital, stumpage value and intermediate supply) and imports from all sectors.

The model was calibrated by constructing a social accounting (SAM) matrix for the New Brunswick economy in 2015, using Statistics Canada's symmetric input-output tables (Statistics Canada 2015). The "detail level" data are used, which breaks the provincial economy into more than 200 sectors. We aggregate this data into the 27 sectors shown in Table 1.

For each sector in the SAM, data is compiled for inputs and outputs, labour, capital, imports, exports and final demand which includes consumption, government consumption and investment. Labour is measured as the sum of wages, salaries, and supplementary labour income, in addition to 'mixed income' (i.e., income of unincorporated businesses). Capital is measured as the sum of other operating surplus, indirect taxes on products, subsidies on products, other subsidies on production, and other indirect taxes on production. Stumpage value is measured as the payments made to forest landowners (both Crown and private landowners) to access and harvest standing trees.

While the New Brunswick 2015 input-output table provides most of the required data to complete the SAM, it does not specially include hardwood and softwood stumpage values. Rather, stumpage payments in the forestry and logging sectors are embedded in each sector's 'other operating surplus' as a component of capital. To isolate stumpage values as inputs, we built on Ochuodho and Lantz (2014) by using total revenue estimates from the sale of stumpage on provincial Crownland (National Forestry Database, 2015) as the starting point for calculating total stumpage revenues. We proportion this revenue into hardwood and softwood stumpage value using the percentage breakdown of volume harvested of each species-type on Crownland in 2015 (NRCan 2020). We then scale-up these Crown land stumpage revenue estimates by adding private land stumpage revenues, based on the percentage of private land volume harvested of each species-type from the total in New Brunswick in 2015 (NRCan 2020).[4]

In order to disaggregate the forestry and logging sector into hardwood forestry & logging and softwood forestry & logging we used the quantity of wood harvested by species and grade (National Forestry Database, 2015), regional stumpage prices per species and grade (New Brunswick Federation of Woodlot Owners, 2015), and New Brunswick's 2015 Supply and Use table (Statistics Canada, 2018). The Supply and Use table includes the dollar value of inputs used by each sector in the economy. In the case of forestry-related sectors, it shows the total dollar value spent on wood harvested. We begin by multiplying the quantity of wood harvested by species and grade by their corresponding price, which provides an estimate of the total and

[4] This method is based on the assumption that private land stumpage rates are the same as those on Crownland, which is the policy of the Provincial government (NBFPC 2016).

proportional value of wood harvested by species and grade in New Brunswick for 2015. We then multiply the proportional value of wood harvested by species and grade by the dollar value spent on wood to estimate the total and proportional dollar value spent by each sector on each species. We aggregate the species-specific spending to provide an estimate of the sector-specific proportion of dollars spent on softwood vs hardwood forestry & logging sectors. These proportions are then applied to New Brunswick's 2015 Input-Output table in order to disaggregate the intermediate demand of various sectors from the hardwood and softwood forestry & logging sectors.

The above adjustments created an imbalance within the SAM. To rebalance the SAM, we created a linear solver that redistributed the imbalance as a fixed proportion to the interactions occurring between the individual forestry & logging sectors and all non-forestry related sectors and entities. This process not only allowed us to balance the SAM but also create a SAM that has unique inputs and outputs for the both the hardwood and softwood forestry & logging sectors. Table 2 provides a summary of the resulting 2015 demand for softwood and hardwood forestry & logging sector intermediate goods by sector used in the SAM.

Table 2. Demand for softwood & hardwood intermediate goods by sector ($ millions, 2015)

	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

In addition to the baseline data outlined above, several other variables and parameters are estimated to accurately reflect the economy of New Brunswick in the base year. Data such as trade balance, household and government savings, and transfers come from Statistics Canada's input-output tables. Elasticity parameters, including income elasticity, elasticity of substitution, and elasticity of transformation, are derived from the GTAP database (GTAP 2018) and Withey et al. (2016)[5].

We use the General Algebraic Modeling System software with a nonlinear programming algorithm, along with CONOPT3 solver (GAMS 2018), to implement the model. The model is initially solved in static form to replicate 2015 data. Checks are conducted to ensure that the model solves without infeasibilities with zero iterations, that the model is square, that Walras law is satisfied, that the model is homogenous of degree zero, and that base year data is replicated.

Following the static general equilibrium solution, the model is solved recursively over a 90-year (2015-2105) time frame. Recursive dynamics is incorporated in the model through growth in capital supply, labour supply, stumpage value and total factor productivity. Capital supply growth is endogenously governed by a capital accumulation equation, which uses an endogenous return rate on capital and total savings (Ochuodho and Lantz 2014). Labour supply is assumed to grow by 0% annually in the model, based on labour supply growth projections from Statistics Canada (Statistics Canada 2020c).[6] Stumpage value growth will depend on the various scenarios considered in our analysis (discussed below).

---

[5] Following Withey et al. (2016), we simply assumed relatively low substitution elasticities between stumpage and capital/labour since published data is not available for these parameters. This is a typical assumption in forest-related CGE studies on grounds that stumpage is largely a required factor in the production of forestry & logging sector output.

[6] For sensitivity analysis purposes, we also consider a positive growth scenario in labour supply of 0.5% annually, and present these results in Appendix I.

As factor inputs change over time, the economy will expand/contract through changes in production, income and final demand, leading to changes in GDP, employment, prices, etc. In our analysis, we focus on changes to key macroeconomic variables such as income, consumption, GDP, equivalent variation[7], exports, imports, and production by sector. Values are presented annually and in present value, real terms ($2015) using a 2% real discount rate (reflecting the historical rate of return of long-term government bonds).

Coupling the models:

Once calibrated with a set of climate, forest, and management parameters (scenarios will be described below), the Woodstock model is run over the 2020-95 period, and produces estimates of hardwood and softwood harvest (in terms of m^3) on New Brunswick's Crownland, which represents approximately 50% of forestland in the Province. Since our intention is to assess the impacts of climate change on the entire Province's forests, we need to scale-up the harvest estimates. We initially investigated extending a private land Woodstock model currently under development by NBERD, however, after a thorough review of the model, we felt the uncertainties in management actions, particularly for private woodlots, would limit our confidence in the model output. Instead, we make a simplifying assumption that our estimated timber production changes over time on Crownland in New Brunswick are representative of the entire forest land base of the province. That is, when our model predicts that Crownland timber supply changes by a certain percentage, we assume private land timber supply changes by the

[7] Equivalent variation is the change in wealth, at current prices, that would have the same effect on consumer welfare as would the 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.

same percentage, resulting in an equivalent percentage change in total timber supply in the province. While there exist some differences in forest area, forest types and management regimes between ownership types that need to be accounted-for in the future (see Table 3 for a comparison), the assumption made here allows us to proceed with our model coupling analysis.

Table 3. Comparison of Crown and private forest land in New Brunswick

	Crown forest	Private forest
Forest land area (mill ha)[a]	3.1	2.9
SW Harvest (mill m^3, 2019)[a]	3.5	2.7
HW Harvest (mill m^3, 2019)[a]	2.1	1.1
SW dominated growing stock (mill m^3)[b]	156	?
HW dominated growing stock (mill m^3)[b]	90	?
Area in SW Plantations ('000 ha)[c]	454	46
SW Planting (mill seedlings/yr, 2019)[a]	20.1	2.8

[a] NRCan (2020).
[b] CCFM (2005).
[c] C. Hennigar, ERD, personal communication, 2021. The private forest plantation estimate excludes freehold areas (representing 18% of NB forest land). Inventory updates are between 1-10 years out of date.

To couple the models, we take the percentage change estimates in softwood and hardwood harvest levels over time produced from the Woodstock model and use them to adjust the hardwood and softwood stumpage value inputs in the CGE model over the same period of time.

Scenarios:

We consider 4 scenarios in our analysis, as summarized in Table 4.[8] Scenario 1 is the Baseline, where labour supply grows at 0% annually, climate change does not occur, planting continues at current rates, and all plantations are assumed to survive. The next three scenarios

[8] As noted above, Appendix I provides a parallel set of scenarios assuming a higher labour supply growth rate.

include different assumptions about climate change, its effects on forest succession/plantations, and options to adapt. In each of these scenarios, we consider only the most extreme IPCC climate change condition, namely RCP 8.5. We focus on RCP 8.5 in this report because other commonly used IPCC conditions, namely RCP 2.5 and 4.5, showed much smaller impacts on timber supplies over time, and as such, we left them out of the presentation of results (these are available from the authors upon request).

Scenario 2 considers the effects of climate change RCP 8.5 in: (i) altering forest succession such that a number of species (mostly softwoods) will not be successful in naturally regenerating/competing; and (ii) increasing drought conditions such that all spruce plantations established in 2020+ fail due to increased drought conditions.

Table 4. Scenarios considered

Scenarios	Description
Scenario 1 (Baseline)	- Labour supply grows at 0% annually - Climate change does not occur - Planting continues at current rates and all plantations survive
Scenario 2 (Climate Change)	- Baseline labour supply growth - Climate change (via IPCC RCP 8.5) alters forest succession and increases drought conditions - Planting continues at current rates, and all spruce plantations established in 2020+ fail due to increased drought conditions
Scenario 3 (Plant Drought-Resistant Seedlings)	- Baseline labour supply growth - Climate change (via IPCC RCP 8.5) alters forest succession and increases drought conditions - Planting continues at current rates and all plantations established in 2020+ survive due to the use of drought resistant spruce seedlings
Scenario 4 (Plant Hardwood)	- Baseline labour supply growth - Climate change (via IPCC RCP 8.5) alters forest succession and increases drought conditions - Planting begins at current rates and climate resistant commercial HW species (red maple, sugar maple, oak) are planted on failed spruce plantations established in 2020+ as they become available.

Scenario 3 considers the same climate change conditions as Scenario 2, however drought-resistant seedlings are used to successfully maintain all plantations established in 2020+. This adaptation option is being given serious consideration in the recent NSERC funded Silvi21 national project, of which one project involves translocation of current seed sources into the south-east US to identify likelihood of current seedling survival under much warmer conditions and also to select for drought resistant genotypes for future spruce plantations (L. D'Orangeville, UNB, personal communication, 2021).

Scenario 4 also considers the same climate change conditions as Scenario 2, however in this case, climate resistant commercial hardwood species (e.g., red maple, sugar maple, oak) are planted on areas previously planted to spruce as well as other non-commerical/poorly-regenerating areas as they become available. Red maple seedlings in particular have shown to be quite resilient in the face of drought conditions (Vaughan 2021). Hardwood plantations are currently being considered in New Brunswick by the New Brunswick Department of Energy and Resource Development to help achieve both Acadian forest restoration and climate change mitigation goals (C. Hennigar, NB ERD, personal communication, 2021). A key hurdle in widespread implementation of hardwood plantations is cost, as seedlings need to be fenced to prevent browse. Another hurdle is the existing manufacturing capacity and the dependence on strong softwood lumber markets across the province.

Economic impact and cost-benefit analysis:

To assess the economic impacts of climate change without and with adaptation, we present a comparison of the economic variable outcomes produced by the CGE model under Scenarios 2, 3 and 4 with those of Scenario 1 (the Baseline). We present these comparisons in both time-trend figures and tables, the latter which includes current and present values (using a 2% discount rate, reflecting the average historical real return on risk-free Canadian government bonds).

We also present a preliminary cost-benefit analysis of the two adaptation options considered in this analysis (i.e., Scenarios 3 and 4), where the cost is equivalent to the present value financial expenditures needed to implement the adaptation activity, and the benefit is equivalent to the increase in present value welfare (i.e., equivalent variation) over time moving from the climate change Scenario 2 to adaptation Scenario 3 or 4. We present our analysis in terms of cost-benefit ratios and net present values (both using a 2% discount rate, representing the historical average real interest rate of government bonds), with adaptation being supported in cases where the former measure is equal to or greater than 1, and the latter measure is equal to or greater than 0. The cost-benefit ratio measures the cost effectiveness of the investment, while the net present value measures the overall efficiency of the investment.

Costs associated with implementing Scenario 3 (Plant Drought-Resistant Seedlings) are based on a core assumption that the tree improvement workload in New Brunswick would have to double in order to continue the current pace of volume gain improvements while introducing improvement in drought tolerance. The cost increases would be mostly variable but some fixed costs would be associated with infrastructure. Workload increases would include grafting, breeding, field trial establishment and management, data collection, and analysis. A single round of R&D would be required to understand the fundamentals of drought tolerance breeding with Acadian conifer species over the first five years. Specific costs are estimated as follows: (i) additional office, lab, greenhouse space for growing field trials at $500k in first year;

(ii) R&D activities to develop drought tolerance breeding strategy at $400k spread over first 5 years; (iii) salaries, benefits, vehicles, and related costs for additional tree improvement professionals and technicians at $555k/yr; (iv) maintenance and up-keep for the additional office, lab, and related infrastructure at $20k/yr; (v) additional materials and supplies including herbicide, field tags, data recorders, greenhouse supplies for growing field test seedlings, etc. at $45k/yr; and (vi) additional contract work for incremental test sites, including mechanical site prep, weed control, etc. at $15k/yr (Josh Sherrill, Leader of Forest Productivity, JD Irving Ltd, personal communication, 2021).

Costs associated with implementing Scenario 4 (Plant Hardwood) are based on the core assumption that a planting program would require additional silviculture investments to successfully establish hardwood stands. R&D efforts would be required early on to better understand seed procurement and stratification, nursery growing, planting practices, weed control requirements, stand tending, and growth and yield to create silviculture best management practices and achieve desired commercial product outcomes. Specific costs are estimated as follows: (i) R&D activities to develop hardwood silviculture program, including program leader, research staff, field studies, data analysis, and reporting at $800k, spread over first 5 years; (ii) incremental seedling costs at $12.52 mill/yr[9]; (iii) incremental planting costs at

[9] Calculated as the difference between the cost of growing hardwood vs conifer seedlings. Here, we assume conifer seedling growing costs are $0.18/tree, conifter planting density is 1,800 trees per ha, hardwood seedling growing costs are $0.38/tree, and hardwood planting density is 2,500 trees per ha (to account for anticipated survival issues). Since there is currently 10,000 ha of forest planted on Crownland annually, and Crownland is approximately 50% of all forested area in the province, we assumed that 20,000 ha of forestland would be planted annually as hardwood plantations over the 2021-2095 period.

$2.5 mill/yr[10]; and (iv) incremental silviculture costs at $10 mill/yr[11] (Josh Sherrill, Leader of Forest Productivity, JD Irving Ltd, personal communication, 2021).

3. Results

Wood supply impacts:

Figures 1 and 2 provide hardwood and softwood timber supply estimates produced by the Woodstock model from 2015 to 2095 under the different scenarios considered. Hardwood timber supply trend is similar and constant over time under all scenarios except under Scenario 4 (Plant Hardwood), where it increases up to 26% by 2095 relative to the Baseline, as hardwood plantations start to mature. Softwood timber supply, on the other hand, is reduced below the Baseline under all other scenarios. The largest decrease is observed under Scenario 2 (Climate Change) where softwood timber supply is reduced by up to 26% below the Baseline by 2095. The reduction of softwood timber supply is surprisingly less significant under Scenario 3 (Plant Hardwood), where it is only reduced by up to 10% below the Baseline by 2095 (one would have expected similar reductions under Scenarios 2 and 3). Further investigation into the cause of this in the Woodstock model reveals that there is a significant amount of spruce-fir ingrowth under Red Maple and Tolerant hardwood plantation yields. Finally, the softwood timber supply reduction is much less under Scenario 4 (Plant Drought-Resistant Seedlings) compared to

[10] Calculated as the difference between the cost of planting hardwood vs conifer seedlings. Here, since hardwood seedlings are larger, we assume it would cost an additional $0.05/tree to plant. This was multiplied by a hardwood planting density of 2,500 trees/ha, and then by 20,000 ha of forestland planted annually as hardwood plantations over the 2021-95 period.
[11] Calculated as 2 additional weed control treatments at $250/ha for each treatment, and multiplied by 20,000 ha of treated forestland annually.

Scenario 2 (Climate Change), where it is reduced by only up to 5% below the Baseline by 2095. This reduction emerges from the climate-induced change in successional dynamics which cause some softwood stands that are not planted to fail.

Figure 1. Hardwood timber supply (m^3 mill)

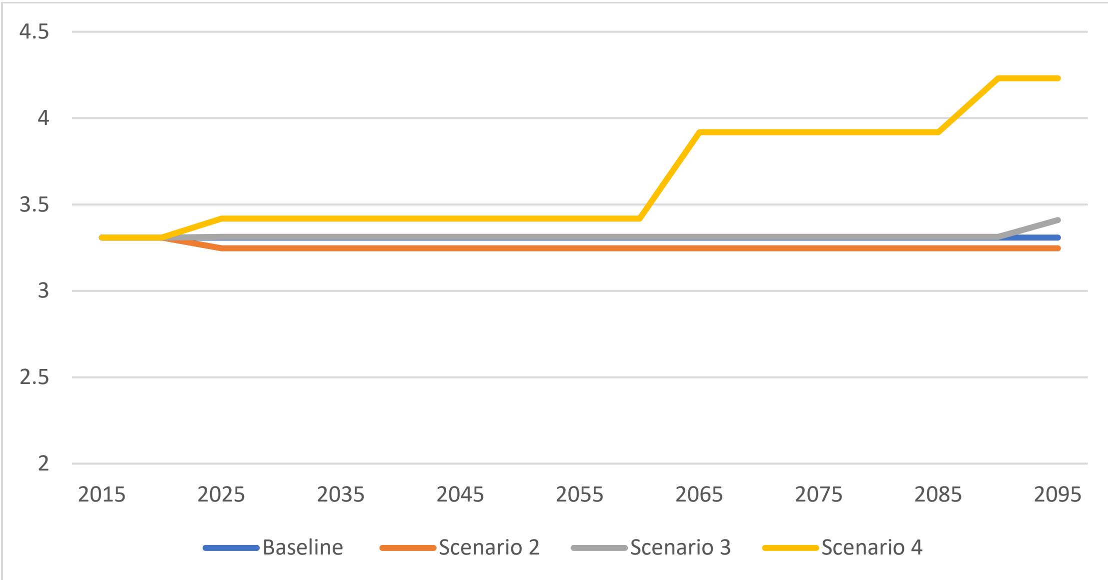
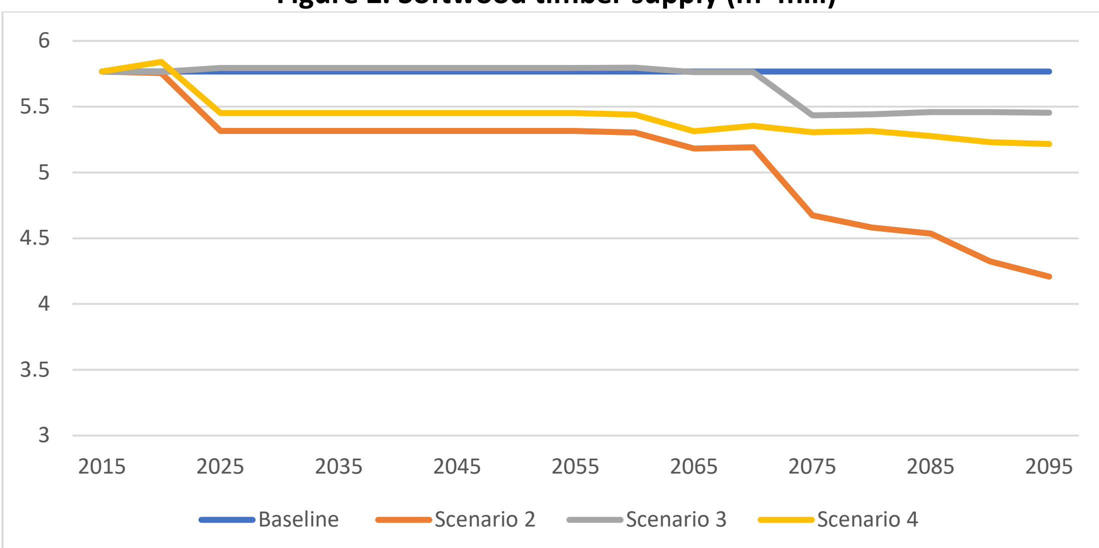


Figure 2. Softwood timber supply (m^3 mill)



Economic impacts:

Figures 3 and 4 provide hardwood and softwood stumpage price estimates produced by the CGE model from 2015 to 2095 under the different scenarios considered. These generally follow the inverse of the respective timber supply trends, where for instance hardwood prices decline under scenarios that exhibit hardwood timber supplies increase, and vice-versa for softwood. This is a result of market demand and supply conditions – when timber becomes more scarce, its price increases, and vice-versa. Overall, Scenario 4 (Plant Hardwood) exhibits the largest hardwood stumpage price decrease at 75% relative to the Baseline by 2095. Scenario 2 (Climate Change) exhibits the largest softwood price increase at 3.5 times the Baseline by 2095.

Figure 3. Hardwood stumpage price ($nominalized, relative to 2015)

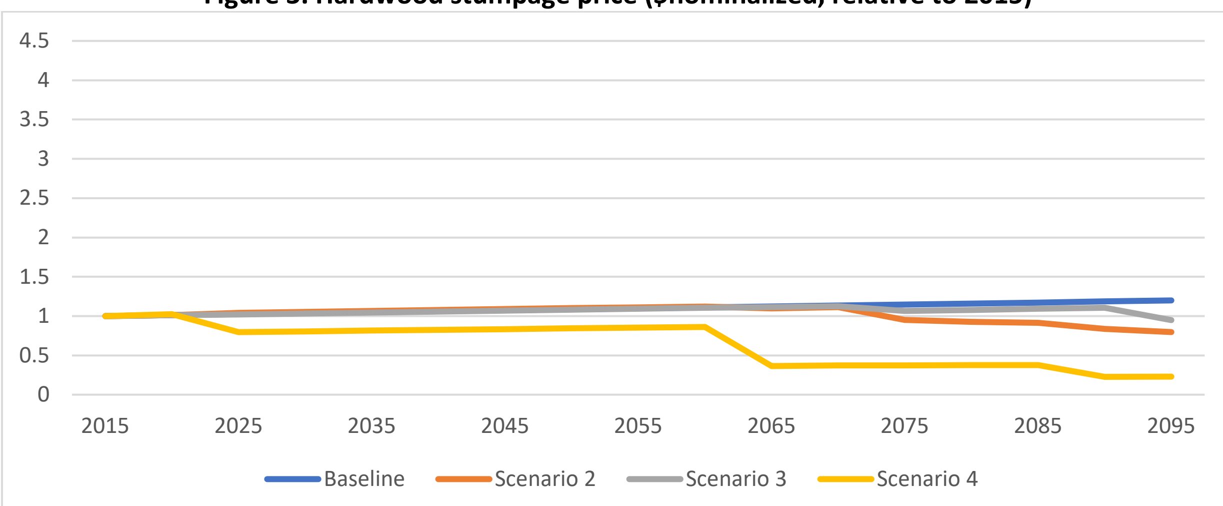


Figure 4. Softwood stumpage price ($nominalized, relative to 2015)

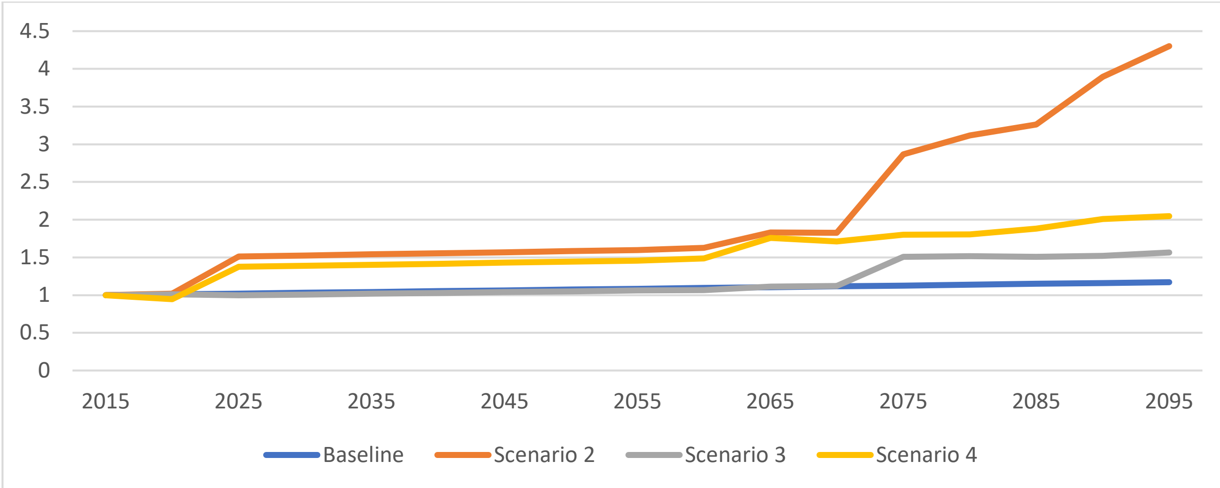
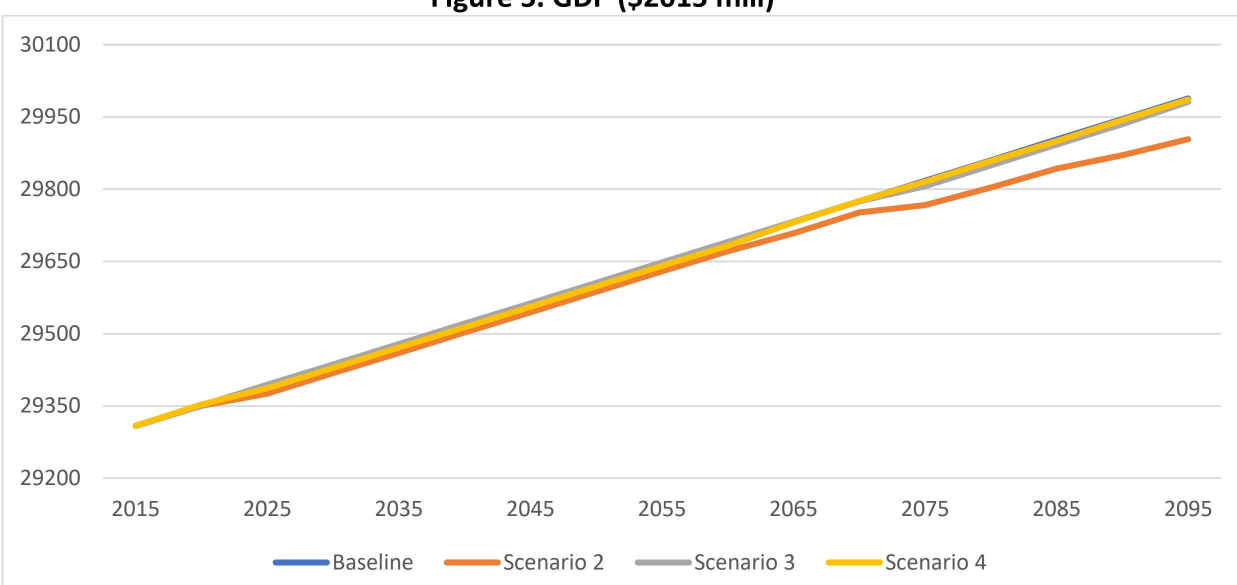


Figure 5 provides GDP estimates produced by the CGE model from 2015 to 2095 under the different scenarios considered. While Scenarios 1, 3 and 4 exhibit similar GDP trends over time, Scenario 2 (Climate Change) exhibits a largest decrease in GDP of approximately 0.28% relative to the Baseline by 2095.   This decline is a result of the significant decrease in softwood timber supply (Figure 2) and corresponding decrease in forest-related sector activity (Table 5 and 7) under this scenario compared to the others.

Figure 5. GDP ($2015 mill)



Tables 5, 6, and 7 provide the sector-level output quantity, output price, and output value estimates by scenario in 2095, respectively. In Table 5, softwood forestry & logging sector output quantity is reduced by 12% under Scenario 2 (Climate Change) relative to the baseline. Additionally, the output quantity of most forestry related manufacturing sectors exhibiting significant declines ranging from 7% to 27% (except paper manufacturing). This follows from the 26% decrease in softwood timber supply in this scenario (see Figure 2). Output quantity in the Hardwood forestry & logging sector and the Pulp manufacturing sector is increased by approximately 2% under Scenario 4 (Plant Hardwood) relative to the Baseline by 2095. This follows from the 26% increase in hardwood timber supply in this scenario (see Figure 1).

In Table 6, sector output prices generally follow the inverse of the respective output quantities. This, again, is a result of market demand and supply conditions – when output becomes scarce, its price increases, and vice-versa. Softwood forestry & logging sector output price increases by as much as 5% under Scenario 2 (Climate Change), while Hardwood forestry & logging sector output price decreases by as much as 2.5% under Scenario 4 (Plant Hardwood) by 2095.

In Table 7, sector output values (comprised of a combination of a sector's output quantity and price) differs most under Scenario 2 (Climate Change) compared to the Baseline, with Softwood and Hardwood forestry & logging sectors exhibiting more than 7% declines, and most forestry related sectors exhibiting between 7% to 26% declines by 2095. It's interesting to note that the Hardwood forestry & logging sector output declines by 2% under Scenario 4 (Plant Hardwood), indicating that the price decrease more than offsets the output quantity increase, leading to an overall decrease in output value in this sector.

Table 5. Sectoral <u>output quantity</u> (measured at 2015 prices) by scenario in 2095 (in % difference from Baseline)

	Scenarios			
Sector	**Baseline ($ millions)**	**Scenario 2 (% diff)**	**Scenario 3 (% diff)**	**Scenario 4 (% diff)**
CROP	846.0	2.67%	0.21%	0.01%
S-FOR	475.1	-12.94%	-1.50%	-2.16%
H-FOR	192.3	-7.20%	-0.06%	2.35%
FISH	368.7	4.02%	0.33%	0.04%
SUPP	88.6	-8.32%	-0.68%	-0.11%
OILGAS	714.5	3.82%	0.31%	0.02%
UTL	1551.7	-0.87%	-0.05%	0.10%
CONST	4260.0	-0.50%	-0.05%	-0.03%
SAW-MANUF	886.2	-13.29%	-1.51%	-2.11%
VEN-MANUF	202.5	-29.34%	-5.21%	-11.78%
OW-MANUF	186.1	-11.21%	-1.76%	-4.04%
PUP-MANUF	1423.3	-7.45%	-0.03%	2.49%
CP-MANUF	495.8	-8.33%	-0.02%	2.85%
PR-MANUF	24.6	-0.09%	0.05%	0.23%
OTH-MANUF	14717.6	3.49%	0.28%	0.02%
TRADES	1693.6	0.39%	0.03%	-0.01%
RET	3124.3	-0.32%	-0.03%	-0.02%
TRANSP	3870.6	-1.58%	-0.10%	0.11%
INFO	1414.8	-0.16%	-0.01%	-0.01%
FIN	8309.8	-0.34%	-0.03%	-0.01%
PROF	1526.8	-0.24%	-0.02%	0.00%
ADMIN	2091.4	-1.02%	-0.08%	0.01%
EDUC	139.3	-0.48%	-0.04%	-0.01%
HEALTH	1405.6	-0.31%	-0.03%	-0.02%
ENT	373.2	-0.59%	-0.05%	-0.01%
ACC	1479.6	-0.40%	-0.03%	-0.01%
OG&S	1343.3	-0.42%	-0.03%	-0.01%

Figures 6 and 7 provide the import and export value of forestry related sector estimates produced by the CGE model from 2015 to 2095 under the different scenarios considered. While import value trends tend to be similar under all scenarios, export value trends tend to vary quite substantially, with export values under Scenario 2 (Climate Change) decreasing by up to 10% relative to the Baseline by 2095. This results largely from the decline in softwood timber harvest and forest related output value under this scenario.

Table 6. Sectoral <u>output prices</u> by scenario in 2095 (in % difference from Baseline)

	Scenarios		
Sector	**Scenario 2 (% diff)**	**Scenario 3 (% diff)**	**Scenario 4 (% diff)**
CROP	0.21%	0.02%	0.01%
S-FOR	5.44%	0.74%	1.59%
H-FOR	-1.01%	-0.71%	-2.98%
FISH	0.11%	0.01%	0.00%
SUPP	0.12%	0.01%	0.01%
OILGAS	0.18%	0.02%	0.01%
UTL	0.21%	0.02%	0.01%
CONST	0.27%	0.03%	0.04%
SAW-MANUF	2.35%	0.30%	0.58%
VEN-MANUF	1.45%	0.19%	0.37%
OW-MANUF	1.36%	0.18%	0.36%
PUP-MANUF	0.92%	0.05%	-0.11%
CP-MANUF	1.13%	0.04%	-0.20%
PR-MANUF	0.38%	0.02%	-0.04%
OTH-MANUF	0.32%	0.03%	0.01%
TRADES	0.13%	0.01%	0.01%
RET	0.11%	0.01%	0.01%
TRANSP	0.13%	0.01%	0.01%
INFO	0.17%	0.02%	0.01%
FIN	0.11%	0.01%	0.01%
PROF	0.09%	0.01%	0.00%
ADMIN	0.10%	0.01%	0.01%
EDUC	0.09%	0.01%	0.01%
HEALTH	0.12%	0.01%	0.01%
ENT	0.12%	0.01%	0.01%
ACC	0.16%	0.01%	0.01%
OG&S	0.11%	0.01%	0.00%

Table 7. Sectoral <u>output value</u> by scenario in 2095 (in % difference from Baseline)

	Scenarios			
Sector	**Baseline ($ millions)**	**Scenario 2 (% diff)**	**Scenario 3 (% diff)**	**Scenario 4 (% diff)**
CROP	837.8	2.89%	0.23%	0.02%
S-FOR	472.0	-8.20%	-0.77%	-0.61%
H-FOR	191.5	-8.13%	-0.76%	-0.70%
FISH	364.7	4.13%	0.34%	0.04%
SUPP	87.7	-8.21%	-0.67%	-0.10%
OILGAS	708.0	4.02%	0.33%	0.03%
UTL	1538.4	-0.67%	-0.03%	0.12%
CONST	4217.0	-0.23%	-0.02%	0.01%
SAW-MANUF	878.7	-11.25%	-1.22%	-1.54%
VEN-MANUF	200.7	-28.31%	-5.03%	-11.45%
OW-MANUF	184.2	-10.01%	-1.58%	-3.70%
PUP-MANUF	1410.9	-6.60%	0.01%	2.38%
CP-MANUF	491.2	-7.30%	0.02%	2.65%
PR-MANUF	24.3	0.29%	0.07%	0.19%
OTH-MANUF	14585.0	3.83%	0.31%	0.03%
TRADES	1676.9	0.52%	0.04%	0.00%
RET	3092.4	-0.21%	-0.02%	-0.02%
TRANSP	3833.0	-1.45%	-0.09%	0.12%
INFO	1402.2	0.01%	0.00%	0.00%
FIN	8224.2	-0.23%	-0.02%	0.00%
PROF	1510.2	-0.15%	-0.01%	0.00%
ADMIN	2069.8	-0.92%	-0.07%	0.02%
EDUC	137.8	-0.39%	-0.03%	-0.01%
HEALTH	1391.5	-0.20%	-0.02%	-0.01%
ENT	369.4	-0.48%	-0.04%	-0.01%
ACC	1464.6	-0.25%	-0.02%	0.00%
OG&S	1328.8	-0.31%	-0.03%	0.00%

Figure 6. Import value of forestry related sectors ($2015 mill)

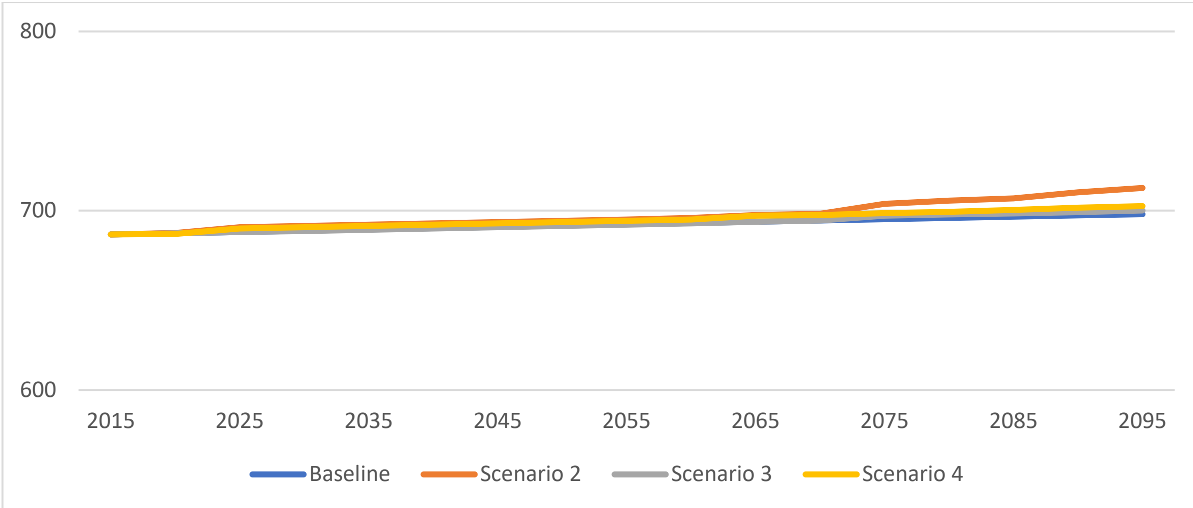
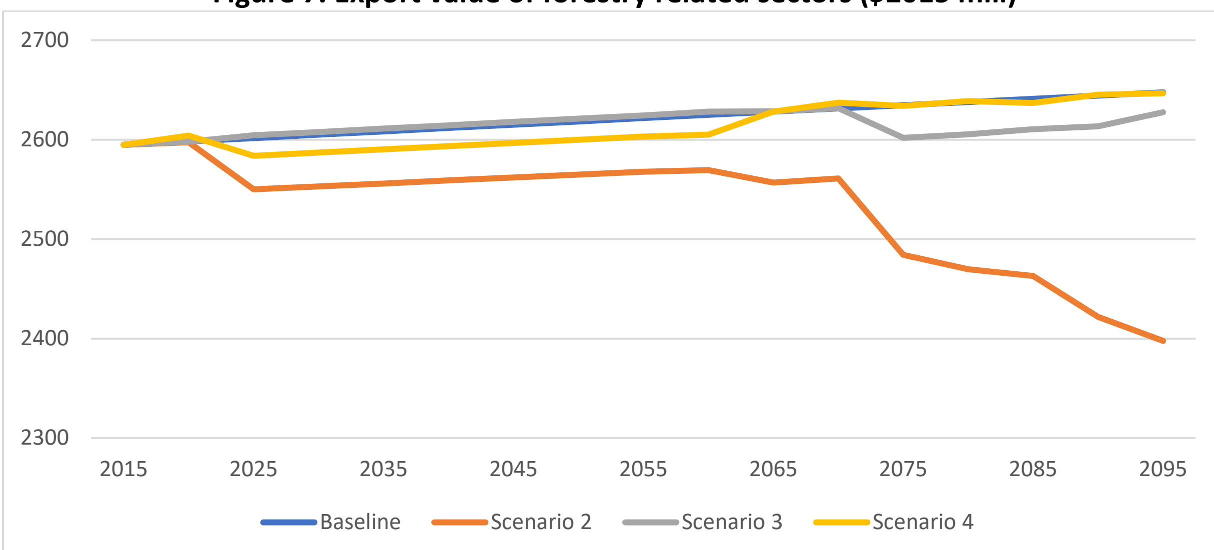


Figure 7. Export value of forestry related sectors ($2015 mill)



Figures 8 and 9 provide the labour and capital expenditure estimates produced by the CGE model from 2015 to 2095 under the different scenarios considered. These macroeconomic variables follow similar trends over time, with Scenario 2 (Climate Change) exhibiting the largest decreases in labour and capital expenditures of 0.42% and 0.07, respectively, by 2095. This results largely from the decline in softwood timber harvest and slowdown in economic activity.

Figure 8. Labour expenditures ($2015 mill)

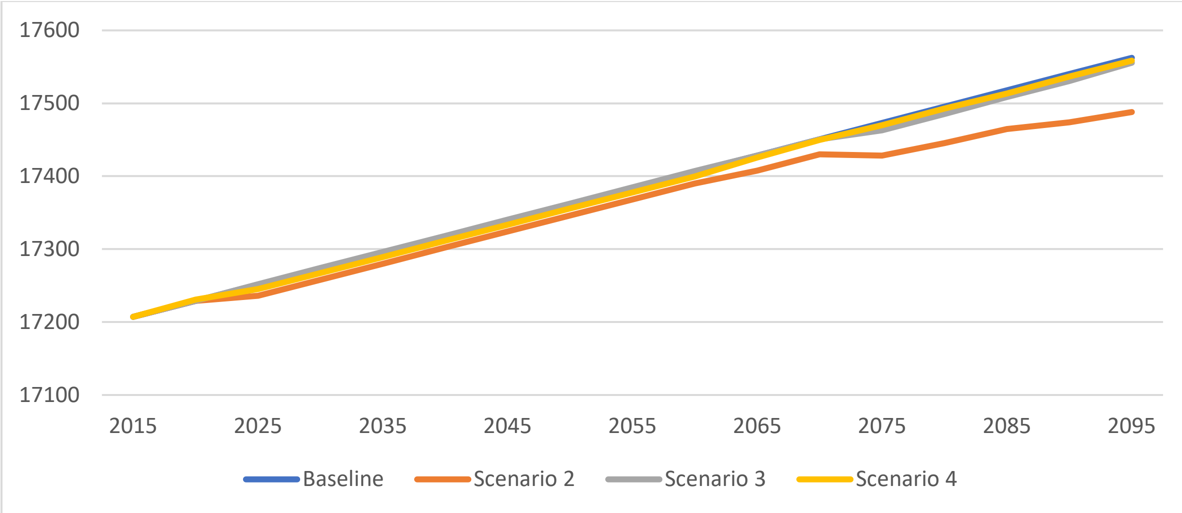


Figure 9. Capital expenditures ($2015 mill)

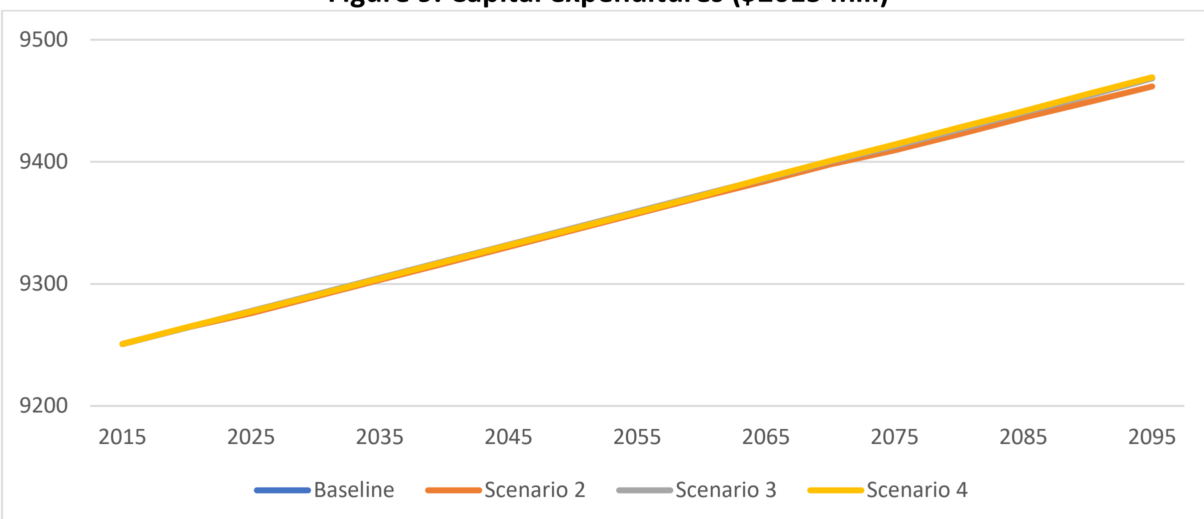


Figure 10 provides unemployment rate estimates produced by the CGE model from 2015 to 2095 under the different scenarios considered. While Scenarios 1, 3 and 4 exhibit similar unemployment rates over time, Scenario 2 (Climate Change) exhibits an increase in the unemployment rate by up to 0.2 percentage points relative to the Baseline by 2095. This results largely from the decline in economic activity and labour demand/expenditures.

Figure 10. Unemployment rate

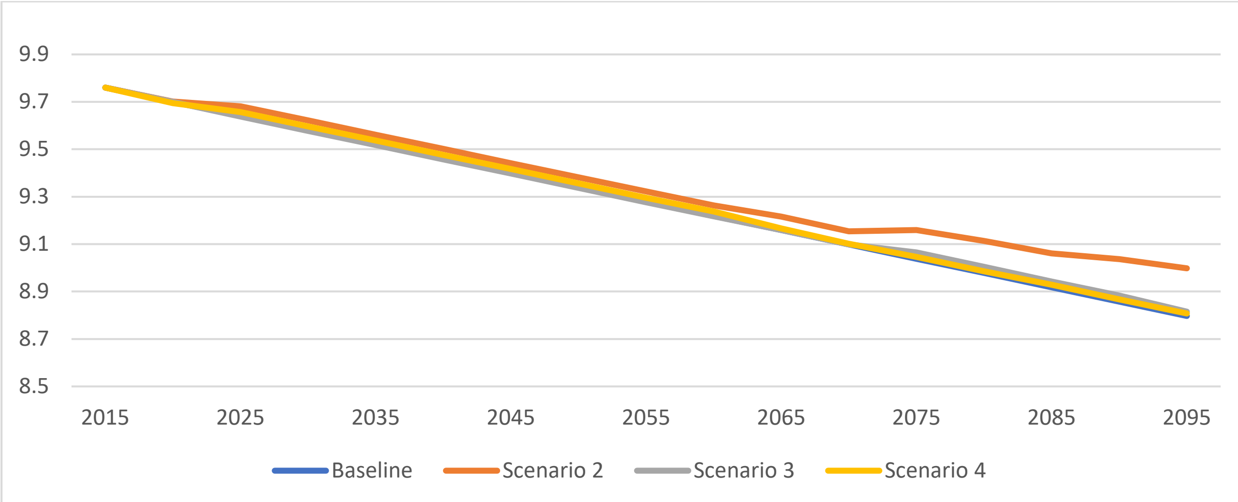


Table 8 presents several macro-economic variables by scenario in 2095. Here it is observed that most GDP components, including consumption, income, government, and exports decline under Scenario 2 (Climate Change) relative to the Baseline. On the other hand, many of these GDP components exhibit increases under Scenario 4 (Plant Hardwood) relative to the Baseline. Similarly, the equivalent variation (EV) variable is most negative under Scenario 2 (Climate Change) and least negative under Scenario 4 (Plant Hardwood).

Table 8. Macro-economic variables by scenario in 2095

Variables	Baseline ($ mill)	Scenario 2 (% diff)	Scenario 3 (% diff)	Scenario 4 (% diff)
GDP	29988.59	-0.28%	-0.02%	-0.01%
EV	453.46	-9.00%	-0.75%	-0.24%
Y	30233.56	-0.13%	-0.01%	0.00%
C	20955.75	-0.13%	-0.01%	0.00%
G	5274.65	-0.25%	-0.02%	-0.02%
L	17562.37	-0.42%	-0.04%	-0.02%
K	9468.81	-0.07%	-0.01%	0.00%
IMP	28969.32	0.42%	0.04%	0.01%
EXP	24399.45	0.54%	0.05%	0.02%
XD	53205.13243	-0.043%	0.00%	0.00%

[a] GDP = gross domestic product; EV = equivalent variation; Y = income; C = consumption; G = government; IMP = imports; EXP = exports; XD = output.

Table 9 presents the cumulative present values of the macro-economic variables from Table 8 by scenario over the 2015-2095 period. While the signs of each variable are generally the same as in Table 8, the percentage differences are much smaller since variable changes that are far off in the future are heavily discounted. Here it is observed that the largest variable declines are again under Scenario 2 (Climate Change) relative to the Baseline.

Table 9. Cumulative present value macro-economic variables by scenario (2015-95, 2% discount rate)

Variables	Baseline ($ mill)	Scenario 2 (% diff)	Scenario 3 (% diff)	Scenario 4 (% diff)
GDP	255241.46	-0.07%	0.00%	-0.01%
EV	1397.81	-6.22%	-0.29%	-1.09%
Y	258615.48	-0.03%	0.00%	-0.01%
C	179253.84	-0.03%	0.00%	-0.01%
G	44786.17	-0.06%	0.00%	-0.01%
L	149717.36	-0.11%	-0.01%	-0.02%
K	80572.40	-0.02%	0.00%	0.00%
IMP	245417.18	0.11%	0.01%	0.02%
EXP	206193.83	0.14%	0.01%	0.02%
XD	450271.268	-0.011%	0.00%	0.00%

Cost-benefit analysis:

Tables 10 and 11 present the cost-benefit analysis of: (i) planting drought resistant softwood seedlings; and (ii) planting hardwoods in place of failed spruce plantations, respectively. For the former adaptation option, the benefit-cost ratio is greater than one and the net present value is greater than 0, indicating that planting drought resistant softwood seedlings would be both cost effective and efficient. The opposite is true for the latter adaptation option, indicating that planting hardwoods in place of failed softwood plantations is neither cost effective or efficient. Therefore, this analysis supports the former over the latter adaptation option.[12]

Table 10. Cost-benefit analysis of planting drought resistant softwood seedlings

Cost or Benefit Item	Estimate
Additional office, lab, greenhouse space for growing field trials, and related infrastructure ($, one-time)	$500,000
R&D activities to develop drought tolerance breeding strategy ($, spread over first 5 years)	$400,000
Salaries, benefits, vehicles, and related costs for additional tree improvement professionals and technicians ($/yr)	$555,000
Maintenance and up-keep for the additional office, lab, and related infrastructure ($/yr)	$20,000
Additional materials and supplies including herbicide, field tags, data recorders, greenhouse supplies for growing field test seedlings, etc. ($/yr)	$45,000
Additional contract work for incremental test sites including mechanical site prep, weed control, etc. ($/yr)	$15,000
Total present value costs[a]	$24,520,000
Total present value benefits[a,b]	$82,900,000
Benefit-cost ratio[a]	3.38
Net present value[a]	$58,380,000

[a] Using a discount rate of 2%.
[b] Using the equivalent variation estimates from the CGE model analysis (see Table 9).

[12] Note here, however, that these are very preliminary estimates, and that we do not factor in the risk associated with the success/failure of either of these programs.

Table 11. Cost-benefit analysis of planting hardwoods in place of failed spruce plantations

Cost or Benefit Item	Estimate
R&D activities to develop hardwood silviculture program, including program leader, research staff, field studies, data analysis, and reporting ($, spread over first 5 years)	$800,000
Incremental seedling cost ($/yr)	$12,520,000
Incremental Planting cost ($/yr)	$2,500,000
Incremental Silviculture cost ($/yr)	$10,000,000
Total present value costs[a]	$932,713,917
Total present value benefits[a,b]	$71,700,000
Benefit-cost ratio[a]	0.08
Net present value[a]	-$861,013,917

[a] Using a discount rate of 2%

[b] Using the equivalent variation estimates from the CGE model analysis (see Table 9).

4. Discussion

In this study, we successfully couple a forest management model with a CGE model to analyze the potential climate change impacts and adaptation on New Brunswick's timber supply and economy. We focus our analysis on the effect that climate change will have on forest succession and the potential failure of spruce plantations. While we find that these climate change effects will have relatively large negative impacts on softwood timber supply (up to a 26% reduction by 2095), softwood forestry & logging sector output quantity (up to a 12% reduction by 2095), and forestry related sector output (ranging from 6% to 27% reduction by 2095), they will have relatively small impacts on GDP (up to a 0.35% reduction by 2095) and the macroeconomic variables that make it up such as consumption, income, and government expenditures. Adapting to these climate-related changes by planting drought-resistant softwood seedlings or hardwood seedlings in place of failed softwood plantations can minimize these negative impacts, and in the latter case, positively impact hardwood timber supply and associated sector output quantity. While the former adaptation option is supported on economic grounds using cost-benefit analysis, the latter is not. The major reasons that planting hardwoods in place of failed softwood plantations is not supported on economic grounds has to do with the large incremental costs of growing, planting, and treating/tending the relatively larger hardwood seedlings to ensure successful growth. If hardwood product values and value-added processing were to increase substantially over time, it could help this adaptation option become more economically viable.

There are a number of caveats that need to be considered when interpreting or relying on the estimates/conclusions in this study. First, we made numerous simplifying assumptions regarding the scaling-up of our Woodstock timber supply modeling of Crownland to all of New Brunswick's forests (which includes Crown and private land). Future analysis needs to include the modeling of private forest land. We also do not consider the potential climate-induced changes in pest, fire, and disease regimes in our analysis. These are widely expected to cause additional negative impacts on forests and timber supplies in the region (Taylor et al. 2017) and should be considered in future analysis.

There are additional caveats when interpreting these results that emanate from our CGE modeling. First, we assume that domestic prices will respond to domestic demand and supply conditions according to calibrated national price elasticities. However, it may be that these elasticity estimates do not apply to a relatively small region such as New Brunswick, where domestic demand and supply conditions (particularly for forest products) don't affect domestic prices to the same extent as they would for larger market economies. Additionally, we don't have data on input factor substitution elasticities in the forestry and logging sectors. Here, we simply assume these to be relatively ‘low’. Different price and input substitution elasticity estimates have the potential to significantly affect the economic impact estimates produced in this study. Therefore, additional primary research into calibrating these elasticity estimates is needed in future studies.

We further caution in the interpretation of our adaptation cost-benefit analyses, as these are based on very preliminary costing estimates provided by industry experts. A more thorough budgeting of the costs associated with developing a drought resistant seedling program and growing/planting hardwood species is needed. Additionally, we do not factor in the risk associated with the success/failure of either of these adaptation programs.

Overall, while our findings should be treated with caution, they provide the first estimates of climate change effects on the forest and the economy using a biophysical/economic modeling framework – namely, a coupled Woodstock and CGE modeling framework. Future studies can expand this analysis to other regions, using either single-region or multi-region CGE models, to help guide decision-making around forest management in the face of a changing climate.

5. References

Banerjee O, Alavalapati J (2009). A computable general equilibrium analysis of forest concessions in Brazil. Forest Policy and Economics 11(4): 244–252.

Boccanfuso D, Savard L, Goyette J, Gosellin V, Mangoua C (2017). An impact analysis of climate change on the forestry industry in Quebec. Canadian Journal of Forest Research 48: 216-226.

Bosello F, Roson R, Tol RSJ (2007). Economy-wide estimates of the implications of climate change: sea level rise. Environmental and Resource Economics 37: 549-571.

Chang Y, Lantz V, Hennigar C, MacLean D (2012). Economic impacts of forest pests: a case study of spruce budworm outbreaks and control in New Brunswick, Canada. Canadian Journal of Forest Research 42: 490-505.

CCFM (2020). National Forestry Database. Wood supply estimates by tenure and species group. Canadian Council of Forest Ministers. Available at: https://cfs.nrcan.gc.ca/publications?id=25854

Corbett LJ, Withey P, Lantz VA, Ochuodho TO (2016). The economic impact of the mountain pine beetle infestation in British Columbia: provincial estimates from a CGE analysis. Forestry 89: 100-105.

Das GG, Alavalapati JRR, Carter DR, Tsigas ME (2005). Regional impacts of environmental regulations and technical change in the US forestry sector: a multiregional CGE analysis. Forest Policy and Economics 7: 25– 38.

Dervis K, de Melo J, Robinson S (1982). General Equilibrium Models for Development Policy. Cambridge University Press, New York.

Dhital N, Raulier F, Bernier PY, Lapointe-Garant M, Berninger F, Bergeron Y (2015). Adaptation potential of ecosystem-based management to climate change in the eastern Canadian boreal forest. Journal of Environmental Planning and Management 58(12): 2228-2249.

D'Orangeville L, Côté B, Houle D, Morin H (2013). The effects of throughfall exclusion on xylogenesis of balsam fir. Tree Physiology 33:516–526.

Dymond C, Giles-Hansen K, Asante P (2020). The forest mitigation-adaptation nexus: economic benefits of novel planting regimes. Forest Policy and Economics 113: 102124.

Fisichelli N, Wright A, Rice K, Mau A, Buschena C, Reich PB (2014). First-year seedlings and climate change: species-specific responses of 15 North American tree species. Oikos 123:1331–1340.

GAMS (2018). General Algebraic Modeling System. GAMS Development Corporation, Washington, DC. Available at: https://www.gams.com/ (accessed: April 1, 2018).

Government of New Brunswick (2015). *New Brunswick Private Woodlot Stumpage Values* (Issue October 2014). Available at https://www2.gnb.ca/content/dam/gnb/Departments/nr-rn/pdf/en/ForestsCrownLands/NBStumpageStudyResults.pdf (accessed: April 1, 2018).

GTAP (2018). Global Trade Analysis Project (GTAP) Database. Available at: https://www.gtap.agecon.purdue.edu/default.asp (accessed: April 15, 2018).

Hope C (2006). The marginal impact of CO2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. Integrated Assessment 6(1): 19-56.

Kemfert C (2002). An integrated assessment model of energy-economy-climate – the model Wiagem. Integrated Assessment 3(4): 281-298.

Lemprière TC, Bernier PY, Carroll AL, Flannigan MD, Gilsenan RP, McKenney DW, Hogg EH, Pedlar JH, Blain D. (2008). The importance of forest sector adaptation to climate change. Natural Resources Canada, Canadian Forest Service, Northern Forest Centre, Edmonton, Alberta. Information Report NOR-X-416.

Liu E, Lantz V, MacLean D, Hennigar C (2019). Economics of early intervention to suppress a potential spruce budworm outbreak on Crown land in New Brunswick, Canada. Forests 10(6): 481-505.

Lundholm A, Black K, Corrigan E, Nieuwenhuis M (2020). Evaluating the impact of future global climate change and bioeconomy scenarios on ecosystem services using a strategic forest management decision support system. Front. Ecol. Evol.; doi:10.3390/10.3389/fevo.2020.00200

Lundholm A, Corrigan E, Nieuwenhuis M (2019). Implementing climate change and associated future timber price trends in a decision support system designed for Irish forest management and applied to Ireland's western peatland forests. Forests 10: 270; doi:10.3390/f10030270

Mendelsohn RO, Morrison WN, Schlesinger ME, Andronova NG (2000). Country-specific market impacts of climate change. Climatic Change 45(3-4): 553-569.

MOSEK (2004). MOSEK product information. Available at: https://www.mosek.com/ (accessed March, 2021).

New Brunswick's Federation of Woodlot Owners. (2015). Stumpage Prices. Available at https://nbwoodlotowners.ca/ (accessed March 2021).

NFPC (2016). Stumpage study results – October 2015 to September 2016. New Brunswick Forest Products Commission. Available at: https://www2.gnb.ca/content/dam/gnb/Departments/nr-rn/pdf/en/ForestsCrownLands/nb_stumpage_study_results_2015-2016.pdf (accessed March 2021).

NBERD (2005). STAMAN v.5.5 user manual. Growth & Yield Unit, New Brunswick Department of Energy and Resource Development, Fredericton, NB, Canada.

Nordhaus WD (1991). To Slow or Not to Slow: The Economics of the Greenhouse Effect. Economic Journal 101(444): 920-937.

NRCan (2020). Statistical Data. Natural Resources Canada. Available at: https://cfs.nrcan.gc.ca/statsprofile/economicimpact/NB (accessed: March 1, 2021).

CCFM (2005). Wood supply in Canada. National Forestry Database Program. Canadian Council of Forest Ministers

Ochuodho TO, Lantz VA, Olale E (2016). Economic impacts of climate change considering individual, additive, and simultaneous changes in forest and agriculture sectors in Canada: A dynamic, multi-regional CGE model analysis. Forest Policy and Economics, 63, 43–51.

Ochuodho TO, Lantz VA (2014). Economic impacts of climate change in the forest sector: A comparison of single-region and multiregional CGE modeling frameworks. Canadian Journal of Forest Research, 44(5), 449–464.

Ochuodho TO, Lantz VA, Lloyd-Smith P, Benitez P (2012). Regional economic impacts of climate change and adaptation in Canadian forests: A CGE modeling analysis. Forest Policy and Economics, 25, 100–112.

Perez-Garcia J, Joyce LA, Binkley CS, McGuire AD (1997). Economic impacts of climate change on the global forest sector: an integrated ecological/economic assessment. Critical Reviews in Environmental Science and Technology 27: 123-138.

Perez-Garcia J, Joyce LA, McGuire AD, Xiao X (2002). Impacts of climate change on the global forest sector. Climatic Change 54: 439–461.

Remsoft (1997). Woodstock forest management software. Remsoft Inc. Available at: https://remsoft.com/woodstock-optimization-studio/ (last accessed Feb 1, 2021).

Sohngen B, Sedjo R (2005). Impacts of climate change on forest product markets: implications for North American producers. Forestry Chronicle 81(5): 669-674.

Sohngen B, Mendelsohn R, Sedjo R (2001). A global model of climate change impacts on timber markets. Journal of Agricultural and Resource Economics 26 (2): 326–343.

Statistics Canada (2015). Provincial symmetric input-output tables. Statistics Canada. Available at: https://www150.statcan.gc.ca/n1/en/catalogue/15-211-X (accessed: April 4 2018).

Statistics Canada. (2015). *New Brunswick's Supply and use table*. Available at https://www150.statcan.gc.ca/n1/pub/15-602-x/2017001/xlsx/15-602-x_2015_eng.zip (accessed: April 4 2018).

Taylor A, Boulanger Y, Price D, Cyr D, McGarrigle E, Rammer W, Kershaw J (2017). Rapid 21st century climate change projected to shift composition and growth of Canada's Acadian Forest Region. Forest Ecology and Management 405: 284-294.

Vaughan W, Taylor A, MacLean DA, D'Orangeville L, Lavigne M (2021). Climate change experiment suggests divergent responses of tree seedlings in eastern North America's

Acadian Forest Region over the 21st century. Canadian Journal of Forest Research (in press: https://doi.org/10.1139/cjfr-2021-0047)

Walters KR (1993). Design and development of a generalised forest management system: Woodstock, in International Symposium on Systems Analysis and Management Decisions in Forestry (Valdivia: Remsoft Inc.).

Williamson T, Colombo S, Duinker P, Gray P, Hennessey R, Houle D, Johnston M, Ogden A, Spittlehouse D (2009). Climate change and Canada's forests: from impacts to adaptation. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. 104 p.

Williamson TB, Price DT, Beverly JL, Bothwell PM, Frenkel B, Park J, Patriquin MN (2008). Assessing potential biophysical and socioeconomic impacts of climate change on forest-based communities: a methodological case study. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Information Report NOR-X-415E.

Zhang J, Alavalapati JRR, Shrestha RK, Hodges AW (2005). Economic impacts of closing national forests for commercial timber production in Florida and Liberty County. Journal of Forest Economics 10: 207–223.

APPENDIX I – Scenario Outcomes with a Labour Supply Growth Rate of 0.5%

Figure A1. Hardwood timber supply (m^3 mill)

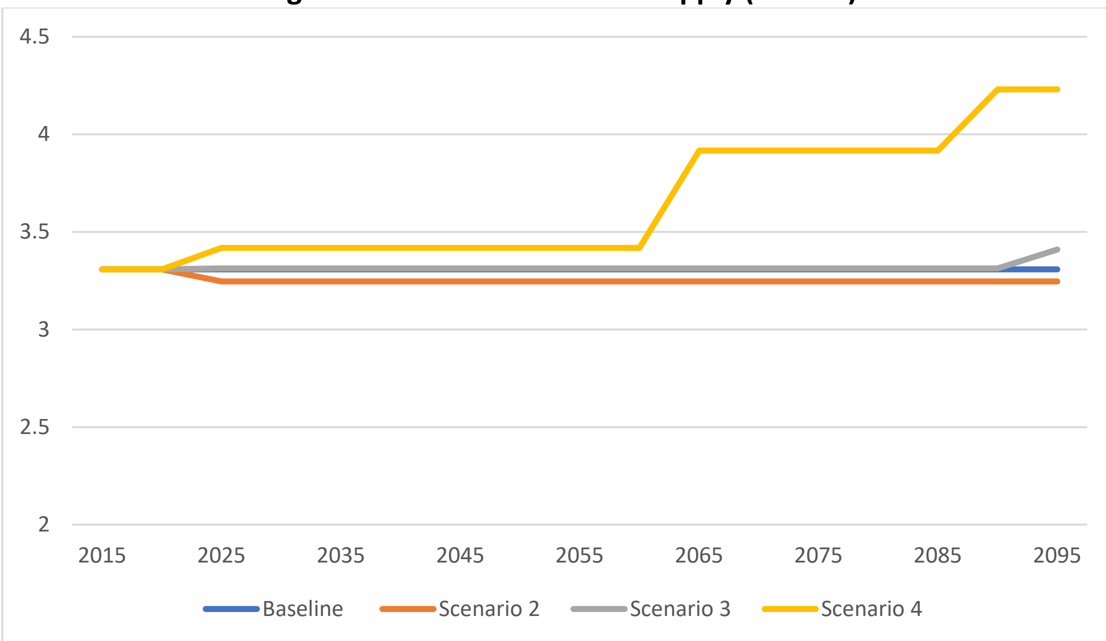


Figure A2. Softwood timber supply (m^3 mill)

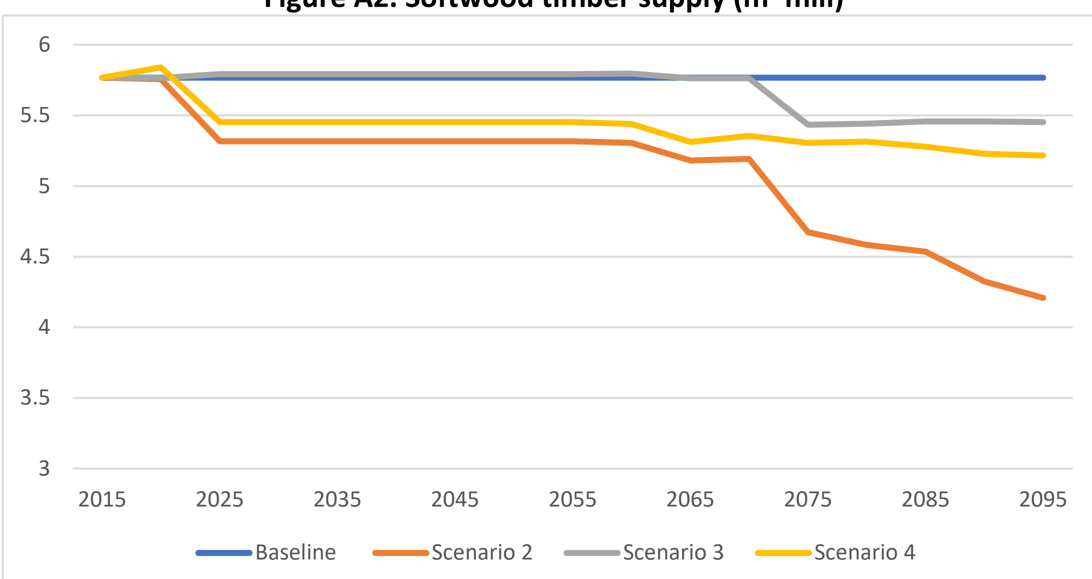


Figure A3. Hardwood stumpage price ($nominalized, relative to 2015)

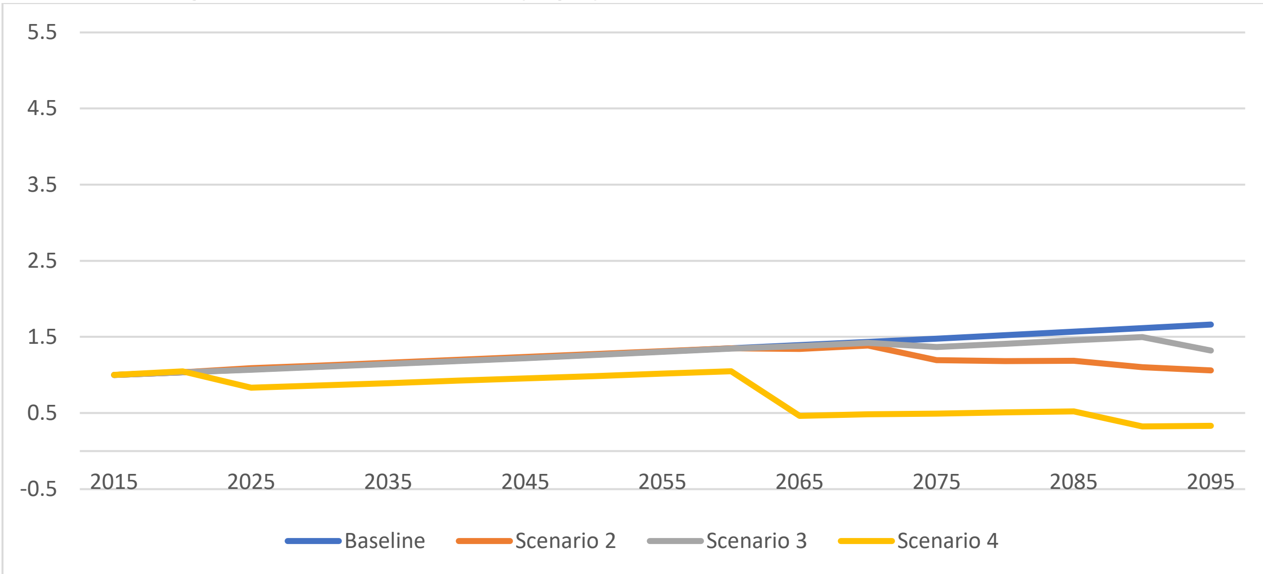


Figure A4. Softwood stumpage price ($nominalized, relative to 2015)

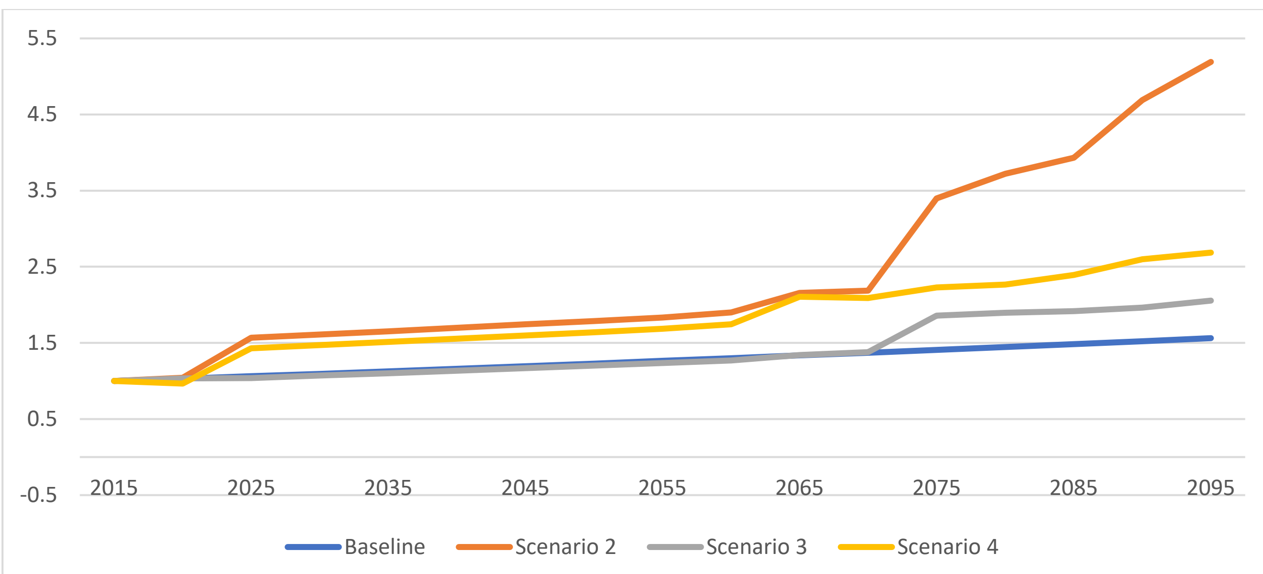


Figure A5. GDP ($2015 mill)

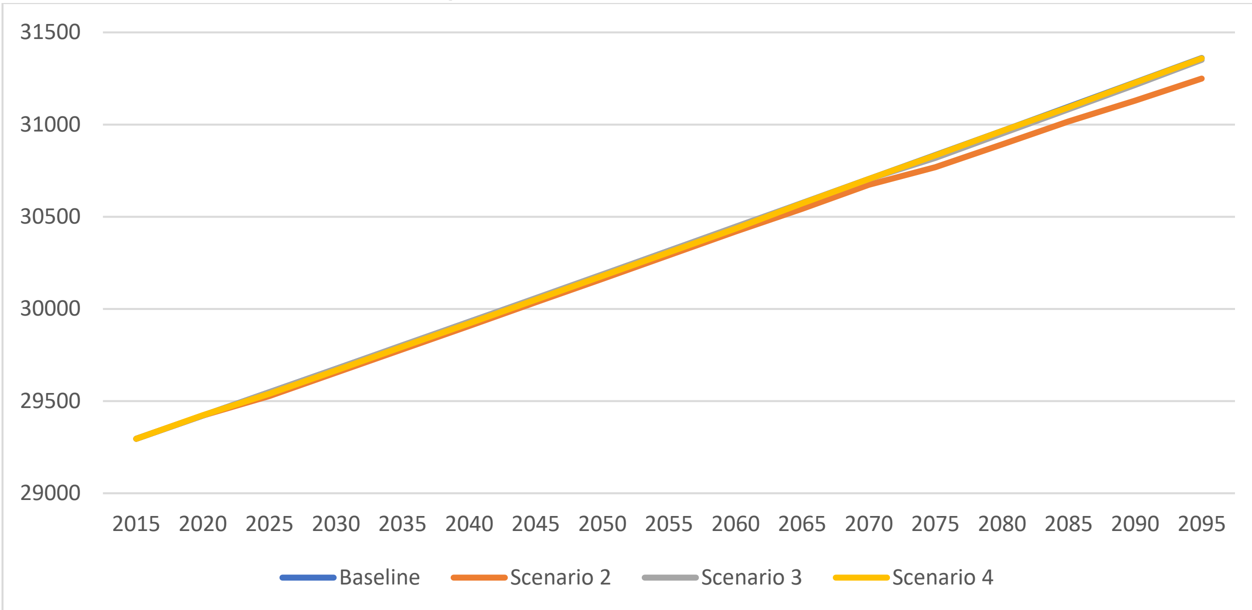


Figure A6. Import value of forestry related sectors ($2015 mill)

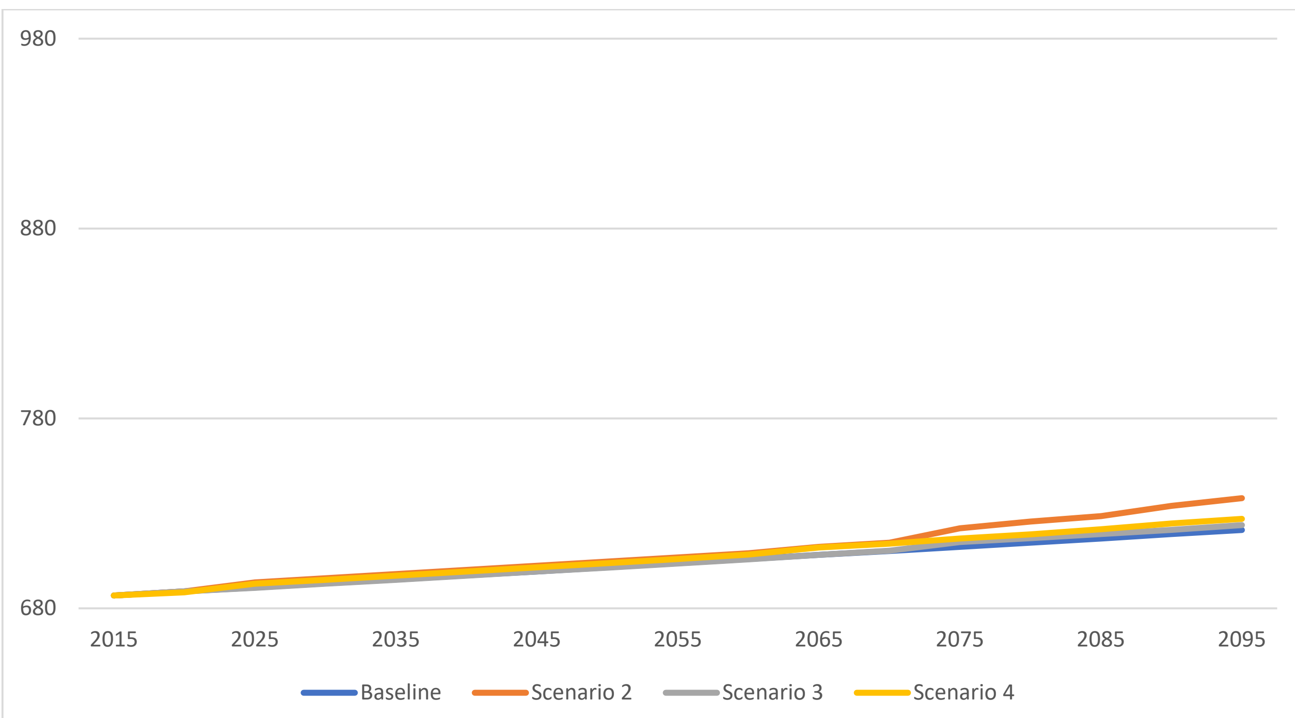


Figure A7. Export value of forestry related sectors ($2015 mill)

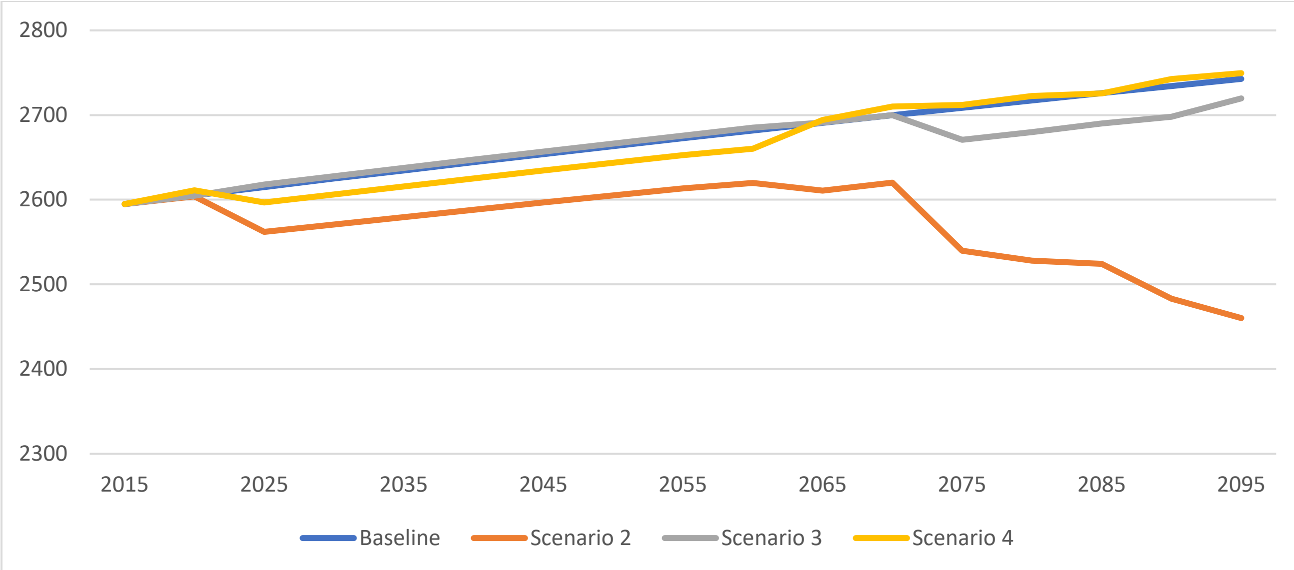


Figure A8. Labour expenditures ($2015 mill)

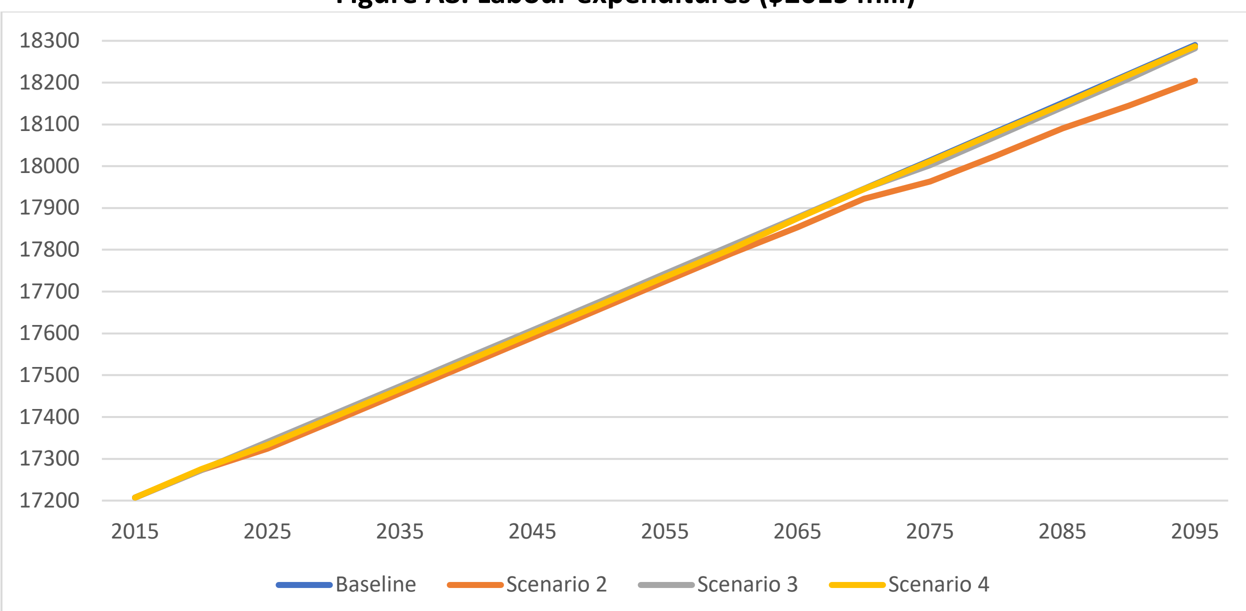


Figure A9. Capital expenditures ($2015 mill)

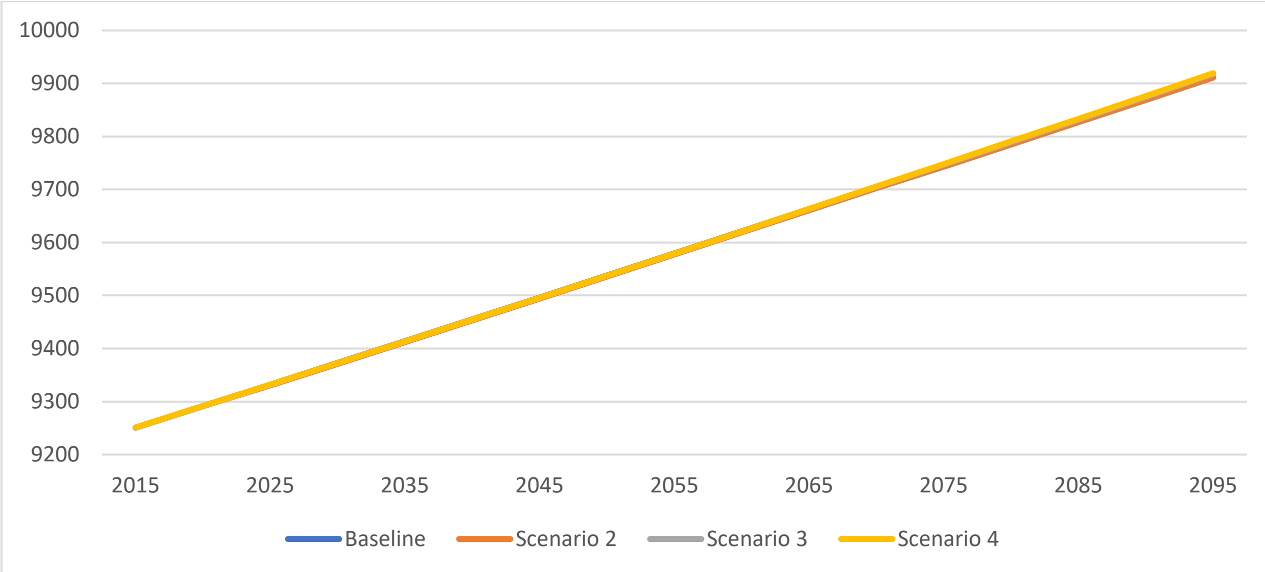


Figure A10. Unemployment rate (% unemployed)

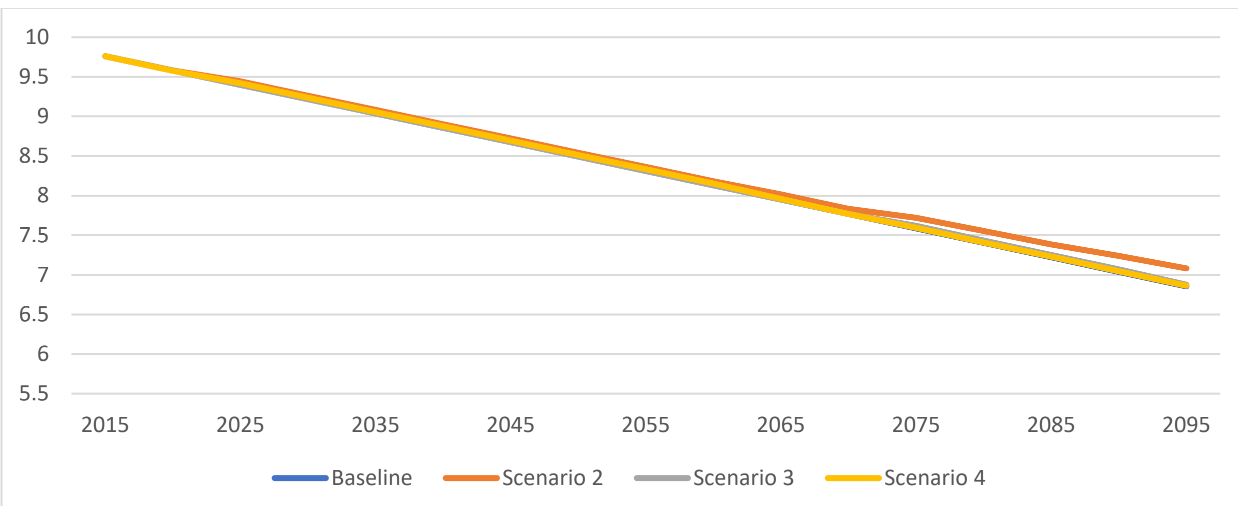


Table A5. Sectoral <u>output quantity</u> by scenario (in % difference from Baseline) in 2095

	Scenarios			
Sector	**Baseline ($ millions)**	**Scenario 2 (% diff)**	**Scenario 3 (% diff)**	**Scenario 4 (% diff)**
CROP	908.7	2.90%	0.24%	-0.07%
S-FOR	506.2	-14.43%	-1.78%	-2.52%
H-FOR	205.0	-7.61%	0.06%	3.38%
FISH	401.3	4.36%	0.36%	-0.07%
SUPP	94.6	-9.12%	-0.76%	0.10%
OILGAS	771.3	4.13%	0.34%	-0.09%
UTL	1644.6	-0.95%	-0.05%	0.17%
CONST	4514.5	-0.56%	-0.05%	-0.02%
SAW-MANUF	945.9	-14.81%	-1.79%	-2.43%
VEN-MANUF	216.5	-32.67%	-6.36%	-14.60%
OW-MANUF	202.7	-12.68%	-2.16%	-5.05%
PUP-MANUF	1526.3	-7.88%	0.09%	3.55%
CP-MANUF	532.6	-8.79%	0.12%	4.05%
PR-MANUF	26.4	-0.09%	0.07%	0.31%
OTH-MANUF	15874.1	3.77%	0.31%	-0.07%
TRADES	1802.6	0.42%	0.03%	-0.03%
RET	3295.5	-0.35%	-0.04%	-0.02%
TRANSP	4099.5	-1.71%	-0.11%	0.19%
INFO	1493.0	-0.18%	-0.02%	-0.01%
FIN	8772.8	-0.38%	-0.03%	0.00%
PROF	1625.3	-0.27%	-0.02%	0.00%
ADMIN	2207.9	-1.10%	-0.09%	0.05%
EDUC	147.4	-0.53%	-0.05%	0.00%
HEALTH	1497.2	-0.35%	-0.03%	-0.02%
ENT	392.3	-0.64%	-0.06%	0.00%
ACC	1560.0	-0.44%	-0.04%	0.00%
OG&S	1420.8	-0.47%	-0.04%	0.00%

Table A6. Sectoral <u>output prices</u> by scenario (in % difference from Baseline) in 2095

	Scenarios		
Sector	**Scenario 2 (% diff)**	**Scenario 3 (% diff)**	**Scenario 4 (% diff)**
CROP	0.24%	0.02%	0.24%
S-FOR	6.18%	0.90%	6.18%
H-FOR	-1.51%	-0.93%	-1.51%
FISH	0.12%	0.01%	0.12%
SUPP	0.14%	0.01%	0.14%
OILGAS	0.20%	0.02%	0.20%
UTL	0.23%	0.02%	0.23%
CONST	0.30%	0.04%	0.30%
SAW-MANUF	2.66%	0.36%	2.66%
VEN-MANUF	1.64%	0.23%	1.64%
OW-MANUF	1.54%	0.22%	1.54%
PUP-MANUF	0.99%	0.05%	0.99%
CP-MANUF	1.22%	0.04%	1.22%
PR-MANUF	0.41%	0.02%	0.41%
OTH-MANUF	0.35%	0.03%	0.35%
TRADES	0.15%	0.01%	0.15%
RET	0.12%	0.01%	0.12%
TRANSP	0.15%	0.01%	0.15%
INFO	0.19%	0.02%	0.19%
FIN	0.12%	0.01%	0.12%
PROF	0.10%	0.01%	0.10%
ADMIN	0.12%	0.01%	0.12%
EDUC	0.10%	0.01%	0.10%
HEALTH	0.13%	0.01%	0.13%
ENT	0.13%	0.01%	0.13%
ACC	0.17%	0.02%	0.17%
OG&S	0.12%	0.01%	0.12%

Table A7. Sectoral output by scenario (in % difference from Baseline) in 2095

	Scenarios			
Sector	**Baseline ($ millions)**	**Scenario 2 (% diff)**	**Scenario 3 (% diff)**	**Scenario 4 (% diff)**
CROP	882.8	3.14%	0.26%	-0.06%
S-FOR	496.8	-9.14%	-0.90%	-0.59%
H-FOR	202.9	-9.00%	-0.87%	-0.68%
FISH	388.3	4.48%	0.37%	-0.07%
SUPP	91.8	-8.99%	-0.75%	0.11%
OILGAS	750.6	4.35%	0.36%	-0.08%
UTL	1602.9	-0.73%	-0.02%	0.18%
CONST	4379.9	-0.26%	-0.02%	0.02%
SAW-MANUF	922.6	-12.55%	-1.43%	-1.74%
VEN-MANUF	210.8	-31.57%	-6.14%	-14.20%
OW-MANUF	196.7	-11.34%	-1.94%	-4.63%
PUP-MANUF	1487.4	-6.97%	0.14%	3.37%
CP-MANUF	518.2	-7.68%	0.16%	3.74%
PR-MANUF	25.6	0.32%	0.09%	0.24%
OTH-MANUF	15451.1	4.14%	0.34%	-0.07%
TRADES	1750.1	0.56%	0.05%	-0.02%
RET	3196.0	-0.23%	-0.02%	-0.02%
TRANSP	3981.6	-1.56%	-0.09%	0.20%
INFO	1453.6	0.01%	0.00%	0.00%
FIN	8505.1	-0.26%	-0.02%	0.01%
PROF	1572.7	-0.17%	-0.01%	0.00%
ADMIN	2140.2	-0.98%	-0.07%	0.05%
EDUC	142.7	-0.43%	-0.04%	0.00%
HEALTH	1452.6	-0.22%	-0.02%	-0.01%
ENT	380.5	-0.51%	-0.04%	0.00%
ACC	1513.1	-0.27%	-0.02%	0.00%
OG&S	1375.7	-0.34%	-0.03%	0.00%

Table A8. Macro-economic variables by scenario in 2095

Variables	Baseline ($ mill)	Scenario 2 (% diff)	Scenario 3 (% diff)	Scenario 4 (% diff)
GDP	31382.58	-0.31%	-0.03%	0.00%
EV	1381.45	-3.38%	-0.29%	-0.03%
Y	31161.64	-0.15%	-0.01%	0.00%
C	21599.03	-0.15%	-0.01%	0.00%
G	5561.64	-0.28%	-0.03%	-0.02%
L	18289.99	-0.47%	-0.04%	-0.02%
K	9918.35	-0.07%	-0.01%	0.01%
IMP	29808.15	1.44%	0.12%	0.00%
EXP	24778.37	1.54%	0.13%	0.01%
XD	56685.07765	-0.049%	0.00%	0.00%

Table A9. Cumulative present value macro-economic variables by scenario (2% discount rate)

Variables	Baseline ($ mill)	Scenario 2 (% diff)	Scenario 3 (% diff)	Scenario 4 (% diff)
GDP	259491.67	-0.08%	0.00%	-0.01%
EV	4230.07	-2.27%	-0.12%	-0.36%
Y	261448.02	-0.04%	0.00%	-0.01%
C	181217.15	-0.04%	0.00%	-0.01%
G	45657.61	-0.07%	0.00%	-0.01%
L	151936.89	-0.12%	-0.01%	-0.02%
K	81938.91	-0.02%	0.00%	0.00%
IMP	30773.22	0.47%	0.04%	0.00%
EXP	26113.27	0.59%	0.05%	0.00%
XD	460777.633	-0.012%	0.00%	0.00%

Table A10. Cost-benefit analysis of planting drought resistant softwood seedlings

Cost or Benefit Item	Estimate
Additional office, lab, greenhouse space for growing field trials, and related infrastructure $ one-time)	$500,000
R&D activities to develop drought tolerance breeding strategy ($ spread over first 5 years)	$400,000
Salaries, benefits, vehicles, and related costs for additional tree improvement professionals and technicians ($/yr)	$555,000
Maintenance and up-keep for the additional office, lab, and related infrastructure ($/yr)	$20,000
Additional materials and supplies including herbicide, field tags, data recorders, greenhouse supplies for growing field test seedlings, etc. ($/yr)	$45,000
Additional contract work for incremental test sites (mechanical site prep, weed control, etc.)	$15,000
Total present value costs[a]	$24,520,000
Total present value benefits[a,b]	$90,900,000
Benefit-Cost Ratio[a]	3.71
Net Present Value[a]	$66,380,000

[a] Using a discount rate of 2%.

[b] Using the equivalent variation estimates from the CGE model analysis (see Table 9).

Table A11. Cost-benefit analysis of planting hardwoods in place of failed spruce plantations

Cost or Benefit Item	Estimate
R&D activities to develop hardwood silviculture program, including program leader, research staff, field studies, data analysis, and reporting ($ spread over first 5 years)	$800,000
Incremental seedling cost ($/yr)	$12,520,000
Incremental Planting cost ($/yr)	$2,500,000
Incremental Silviculture cost ($/yr)	$10,000,000
Total PV costs[a]	$932,713,917
Total PV benefits[a,b]	$80,800,000
Benefit-Cost Ratio[a]	0.09
Net Present Value[a]	-$851,913,917

[a] Using a discount rate of 2%

[b] Using the equivalent variation estimates from the CGE model analysis (see Table 9).

APPENDIX II – CGE Model Description

Table A1. CGE Model Parameters[a]

Parameters	Description
Elasticities	
$\sigma F2_i$	Substitution between factors (capital-labour bundle, hardwood stumpage, and softwood stumpage) within the second nest of the production function
$\sigma F3_i$	Substitution between factors (capital and labour) within the third nest of the production function
σT_i	CET substitution between domestic market and the export market
σA_i	Arrington substation between domestic commodities and imported commodities
Share parameters	
$\gamma KL2_i$	Share parameter for capital-labour bundle in the second nest of the production function
$\gamma TH2_i$	Share parameter for hardwood stumpage in the second nest of the production function
$\gamma TS2_i$	Share parameter for softwood stumpage in the second nest of the production function
$\gamma F3_i$	Share parameter for the third nest of the production function the third nest
γT_i	Share parameter of the CET function and the destination of domestically produced commodities
γA_i	Share parameter of the Arrington function
Efficiency parameters	
$\lambda F1_i$	Efficiency parameter for the factors of production (stumpage-capital-labour) in the first nest of the production function.
$\lambda F2_i$	Efficiency parameter for the factors of production (capital-labour bundle, hardwood stumpage, and softwood stumpage) in the second nest of the production function.
$\lambda F3_i$	Efficiency parameter for the factors of production (capital and labour) in the third nest of the production function.
λA_i	efficiency parameter in the Arrington function
λT_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	
$\alpha HLES_i$	Power in the nested ELES household utility function
αKG	Cobb-Douglass power in the government's capital demand function
αLG	Cobb-Douglass power in the government's labour demand function
αCG_i	Cobb-Douglass power in the government's commodity demand function
αI_i	Cobb-Douglass power in the bank's commodity demand function
Trep	Replacement rate
$io_{i,j}$	Technical coefficient of intermediate input
φ	Philips curve parameter
μH	Households subsistence consumption level
mps	Households marginal propensity to save
Growth rates	
GRL	Growth rate of labour
ψ	Initial real rate of return

[a] i and j indicate sector (1…27) specific values.

Table A2. CGE Model Variables[a]

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
PTS_{t}	Price of softwood stumpage
PK_{t}	Price of capital (rent)
PL_{t}	Price of labour (wages)
$P_{i,t}$	Price of composite commodities
$PD_{i,t}$	Price of domestically produced commodities
$PDD_{i,t}$	Price of domestically produced commodities sold to the domestic market
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

[a] t indicates a time period (2015-95).

Table A3. CGE Model Equations

Equations		**Description**
Production block		
$WKL_{i,t} = \lambda F1_i * XD_{i,t}$	EQ 1.1	Firms' demand for stumpage-capital-labour bundle (1st nest)
$PD_{i,t} * XD_{i,t} = (PWKL_{i,t} * WKL_{i,t}) + \left(\sum_j io_{j,i} * XD_{i,t} * P_{i,t} \right)$	EQ 1.2	Firms' zero profit condition (1st nest)
$KL_{i,t} = \frac{WKL_{i,t}}{\lambda F2_i} * \left(\frac{\gamma KL2_i}{PKL_{i,t}}\right)^{\sigma F2_i} * \left[\left(\gamma KL_i^{\sigma F2_i} * PKL_{i,t}^{(1-\sigma F2_i)}\right) + \left(\gamma TS_i^{\sigma F2} * PTS_t^{(1-\sigma F2_i)}\right) + \left(\gamma TH_i^{\sigma F2} * PTH_t^{(1-\sigma F2_i)}\right)\right]^{\left(\frac{\sigma F2_i}{(1-\sigma F2_i)}\right)}$	EQ 1.3	Firms' demand for capital-labour bundle
$TH_{i,t} = \frac{WKL_{i,t}}{\lambda F2_i} * \left(\frac{\gamma TH2_i}{PTH_t}\right)^{\sigma F2_i} * \left[\left(\gamma K_i^{\sigma F2_i} * PKL_{i,t}^{(1-\sigma F2_i)}\right) + \left(\gamma TS_i^{\sigma F2} * PTS_t^{(1-\sigma F2_i)}\right) + \left(\gamma TH_i^{\sigma F2} * PTH_t^{(1-\sigma F2_i)}\right)\right]^{\left(\frac{\sigma F2_i}{(1-\sigma F2_i)}\right)}$	EQ 1.4	Firms' demand for hardwood stumpage (2nd nest)
$TS_{i,t} = \frac{WKL_{i,t}}{\lambda F2_i} * \left(\frac{\gamma TS2_i}{PTS_t}\right)^{\sigma F2_i} * \left[\left(\gamma KL_i^{\sigma F2_i} * PKL_{i,t}^{(1-\sigma F2_i)}\right) + \left(\gamma TS_i^{\sigma F2} * PTS_t^{(1-\sigma F2_i)}\right) + \left(\gamma TH_i^{\sigma F2} * PTH_t^{(1-\sigma F2_i)}\right)\right]^{\left(\frac{\sigma F2_i}{(1-\sigma F2_i)}\right)}$	EQ 1.5	Firms' demand for softwood stumpage (2nd nest)
$PWKL_{i,t} * WKL_{i,t} = \left((PKL_{i,t} * KL_{i,t}) + (PTH_t * TH_{i,t}) + (PTS_t * TS_{i,t})\right)$	EQ 1.6	Firms' zero profit condition (2nd nest)
$K_{i,t} = \frac{KL_{i,t}}{\lambda F3_i} * \left(\frac{\gamma F3_i}{(1+tk_i) * PK_t}\right)^{\sigma F3_i} * \left[\left(\gamma F3_i^{\sigma F3_i} * ((1+tk_i) * PK_t)^{(1-\sigma F3_i)}\right) + \left((1-\gamma F3_i)^{\sigma F3_i} * ((1+tl_i) * PL_t)^{(1-\sigma F3_i)}\right)\right]^{\left(\frac{\sigma F2_i}{(1-\sigma F2_i)}\right)}$	EQ 1.7	Firms' demand for capital (3rd nest)
$L_{i,t} = \frac{KL_{i,t}}{\lambda F3_i} * \left(\frac{(1-\gamma F3_i)}{(1+tl_i) * PL_t}\right)^{\sigma F3} * \left[\left(\gamma F3_i^{\sigma F3_i} * ((1+tk_i) * PK_t)^{(1-\sigma F3_i)}\right) + \left((1-\gamma F3_i)^{\sigma F3_i} * ((1+tl_i) * PL_t)^{(1-\sigma F3_i)}\right)\right]^{\left(\frac{\sigma F2_i}{(1-\sigma F2_i)}\right)}$	EQ 1.8	Firms' demand for labour (3rd nest)
$PKL_{i,t} * KL_{i,t} = \left((1+tk_i) * PK_t * K_{i,t}\right) + \left((1+tl_i) * PL_t * L_{i,t}\right)$	EQ 1.9	Firms' zero profit condition (3rd nest)

Table A3 continued…

Equations		Description
Household block		
$Y_t = PK_t * KS_t + PL_t * (LS_t - UNEMP_t) + TSS_t * PTS_t + THS_t * PTH_t + TRF_t$	EQ 2.1	Household's income
$SH_t = mps * (Y_t - ty * Y_t)$	EQ 2.2	Household's saving
$CBUD_t = (1 - ty) * Y_t - SH_t$	EQ 2.3	Household's consumption expenditure
$(1 + tc_i) * P_{i,t} * C_{i,t} = (1 + tc_i) * P_{i,t} * \mu H_i + \alpha HLES_i * (CBUD_t - \sum_j (\mu H_j * (1 + tc_j) * P_{j,t})$	EQ 2.4	Households' demand for commodities
$\left(\frac{\left(\frac{PL_t}{PCINDEX_t}\right)}{\left(\frac{PL_0}{PCINDEX_0}\right)}\right) = \varphi * \left(\frac{\frac{UNEMP_t}{LS_t}}{\frac{UNEMP_0}{LS_0}} - 1\right)$	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

Table A3 continued…

Equations		Description
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 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

Table A3 continued…

Equations		Description
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