Integration of climate change and development of adaptive capacity for the determination of harvest levels in Quebec

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Integration of climate change and development of adaptive capacity in the determination of harvest levels in Quebec

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Introduction

Climate change can transform ecosystems by modifying their productivity, their composition, and their structure. Many studies have considered the impacts of global changes and have forecast, over the long term, an intensification of forest fire regimes, the migration of tree species and habitats, changes in growing conditions for many boreal forest species, more frequent droughts, and the introduction of invasive species.

Consideration of these changes in the context of forest stewardship is timely and is among the legal dispositions in Quebec's Sustainable Forest Development Act[1]. Indeed, an understanding of the risks associated with climate change and how forest management strategies applied today will influence the forests of tomorrow has become essential.

In Quebec, the principal mission of the Chief Forester is to determine annual allowable cut[2]. In order to do this, the evolution of the forest is modelled over a 150 year period, with assumptions derived from historical data that, therefore, suppose stable environmental conditions. Currently in the context of annual allowable cut determinations, the risks associated with climate change are not taken into account because the required knowledge and compatible methods have not been available.

It is in this context that the project *Integration of climate change and development of adaptive capacity in the determination of harvest levels in Quebec* was submitted in 2017 to the Canada's Climate Change Adaptation Platform of Natural Resources Canada[3] in response to a call for proposal. With oversight by the Chief Forester, the project seeks to develop an approach that leads to better decision-making as it relates to sustainable forests and the selection of the most appropriate adaptation measures given anticipated risks. The two main outcomes expected from this work are:

- A new modelling approach that allows an exploration of the impacts of a number of climate scenarios and strategic decision-making on annual allowable cuts and the sustainability of forest ecosystems
- A decision support system that translates a range of technical modelling results into elements that support the Chief Forester's strategic decision-making, as well as tactical and operational considerations for regional forest managers.

The main distinguishing characteristic of the project is the integration of multiple phenomena, both anthropogenic and natural, usually addressed separately in modelling. Also, the linking up of scientific projections with management decisions and administrative processes represents a significant organisational challenge.

The project took place between April 1st 2018 and November 30th 2020. This document reports on the work carried out by the Chief Forester with the participation of many collaborators. The context section describes the project's general environment. The theoretical framework presents the scientific knowledge that was integrated into the project to model forest dynamics under climate change. Subsequent chapters describe methodology, and then results are presented and discussed. Finally, the report makes recommendations for follow up work and suggests how the method could be applied across Quebec and in other Canadian provinces.

[1] La loi sur l'aménagement durable du territoire forestier; http://legisquebec.gouv.qc.ca/en/showdoc/cs/A-18.1 (Chapter V).

[2] Translator's note (TN): Annual allowable cut, or « possibilité forestière » in French, is defined in Quebec as the maximum amount wood volume that can be harvested annually without diminishing forest productivity.

[3] The Canada's Climate Change Adaptation Platform, established in 2012, is a national forum for collaboration among key Canadian groups on climate change adaptation. https://www.nrcan.gc.ca/climate-change/impacts-adaptations/adapting-our-changing-climate/10027

1. Context

The establishment of the *Plan d'action du Québec sur le changements climatiques*[4] *2006-2012* and *2013-2020* generated a significant amount of research work on the potential impacts of climate change on natural systems. Concurrently, others focused on the search for solutions and possible responses to these changes by identifying adaptation or mitigation measures. The main challenge addressed by this project is the integration of such scientific advances to produce information that corresponds to the needs of decision-makers responsible for the management of forest resources and, in particular, the calculation of annual allowable cut. Ultimately, the model developed must be able to adapt to different forestry contexts across the province and allow the comparison of different adaptation measures.

1.1. Legal context, mission of the Chief Forester, and justification for the project

Quebec's Sustainable Forest Development Act defines the roles and responsibilities of the Chief Forester[5]. Given these responsibilities, the Chief Forester must:

- Determine annual allowable cuts
- Establish the methods, means, and tools required to calculate annual allowable cuts for forests on crown land
- Advise the Minister of Forests, Wildlife, and Parks, especially on matters of research and development related to forestry, territorial boundaries and the delineation of forest management units, and the optimisation of forest management strategies.

Expectations have been expressed at the Chief Forester's to take into account the effects of climate change. In particular, Article 48 of the Sustainable Forest Development Act requires annual allowable cuts to be determined so as to ensure the sustainability of forest practices by meeting the following objectives:

- the sustainability of forests
- the impact of climate change on forests
- the natural dynamics of forests, including their composition, age structure and tree distribution pattern
- the maintenance and improvement of the productive capacity of forests, and
- the diversified use of forests.

The *Sustainable Forest Management Strategy*[6], published in 2015, presents six additional challenges for consideration by the Chief Forester:

- Forest management that takes into account the interests, values and needs of the population of Quebec, including aboriginal peoples
- Forest management that ensures ecosystem sustainability
- Productive forests that generate a broad range of benefits
- A forest products industry and forestry companies that are diversified, competitive, and innovative
- Forests and a forestry sector that contribute to climate change mitigation
- Forest management that is sustainable, structured, and transparent.

In 2017, Quebec's Auditor General expressed concerns[7] about the state of progress of the Chief Forester's work because "… *modelling of the impacts of climate change and of natural disturbances on the state and productivity of forest ecosystems has been postponed at the Office of the Chief Forester, and no new deadline has been set.*

[4] TN: Quebec's Action Plan for Climate Change
[5] http://legisquebec.gouv.qc.ca/en/showdoc/cs/A-18.1 (Chapter V, articles 46 paragraph 1 and 48).
[6] https://mffp.gouv.qc.ca/english/publications/forest/sustainable-forest-management-strategy.pdf
[7] https://www.vgq.qc.ca/Fichiers/Publications//rapport-annuel//2017-2018-printemps//fr_Rapport2017-2018-PRINTEMPS-Chap04.pdf (see p. 14, article 51); the cited passage was translated from the French version.

This knowledge is, however, important in order to target the best silvicultural scenarios". Indeed, work on climate change impacts, though they were initiated, were not sufficiently advanced to be taken into account in the annual allowable cut determinations for the 2018-2023 period, announced in 2016.

It is in this context, therefore, that this project was developed, in order to support the Chief Forester by providing relevant information and knowledge on potential impacts and adaptation measures of forests related to climate change.

1.2. Project goal and objectives

The goal of the project *Integration of climate change and development of adaptive capacity for the determination of harvest rates in Quebec* is to initiate the integration of climate change adaptation measures to the process of annual allowable cut determination. This process seeks to develop an approach that improves decision-making with regards to the selection of the most appropriate forest management strategies given anticipated risks. It aims to fulfill the requirements of the Sustainable Forest Development Act and guides the strategic choices made today that will ensure the permanence of forests and a forest industry that is resilient in tomorrow's climate.

More specifically, the objectives of the project were to:

- Develop a regional scale model that integrates the effects of climate change,
- Model the effects of forest management and natural disturbances,
- Develop and test adaptation strategies, and
- Communicate results to support decision-making.

The process undertaken as part of the project does not seek to replace AAC determination. Rather, the process is complimentary and independent, and seeks to inform decision-makers on the risks associated to a range of climate scenarios (Figure 1).

After completion of this project, the approach could be improved (section 5) and applied to all forests on Crown land in Quebec (section 6), which cover over 45 million hectares. The strategic information thus generated could then be integrated into AAC determination and forest management across the Province.

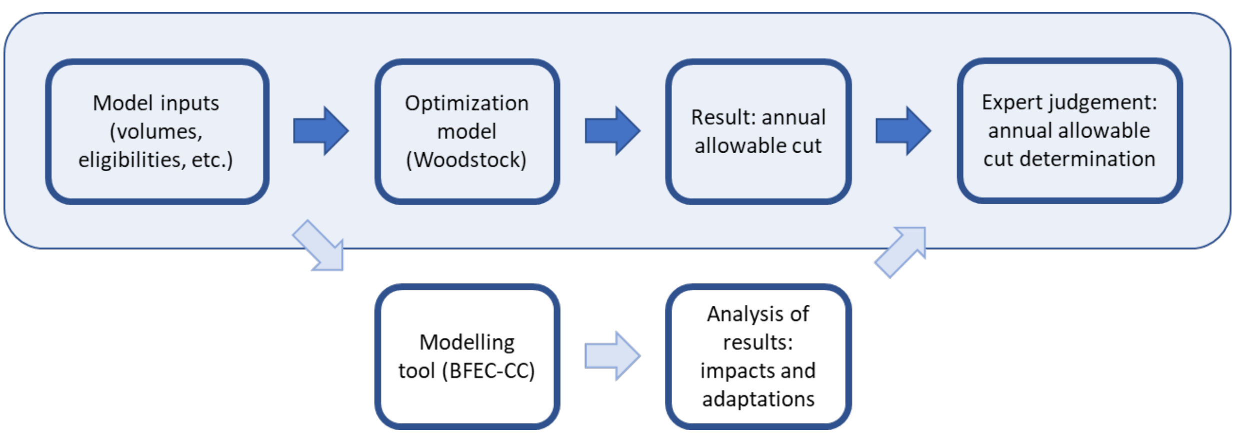


Figure 1. Diagram illustrating the integration of risks linked to climate change into the determination of annual allowable cut. The current process for annual allowable cut determination is enclosed in the blue box.

2. Scientific framework

This section presents the scientific information and concepts on which the project work is based.

2.1. Calculation and determination of annual allowable cut

Annual allowable cut calculation is a modelling exercise projecting forward the effects of management actions on forests over a 150 year period. Currently in Quebec, this modelling is carried out through linear programming, which is a mathematical technique that seeks an optimal solution to a problem stated as an objective function and constraints expressed as linear equations (Davis et al. 2005). The method identifies the forest management strategy that maximizes timber harvest while respecting sustainable forest management objectives (Bureau du forestier en chef 2013). Regional forest management plans are developed by the planners at regional directorates; these plans follow the guidelines set by the department of Forests, Wildlife and Parks but also take into account the wishes expressed by forest stakeholders. In Quebec's process for annual allowable cut determination, regions prepare forest management strategies.

Finally, the annual allowable cut calculation integrates up to date knowledge on the state of the forest, its evolution, and the effects of management. Many constraints are applied in the modelling exercise in order to respect sustainable management objectives and to obtain a sustainable harvest rate.

"A sustained harvest rate is a risk-management measure intended to avoid an over-exploitation of forests and to ensure a stable flow of wood products to the forest industry. To do this, wood volumes harvested today must not cause a decrease in future allow cut rates, and harvest rates must be stable over time." (Bureau du forestier en chef 2013)

The Chief Forester determines annual allowable cuts based on annual allowable cut calculations, the results of an external review of allowable cut calculations, complimentary analyses, and on recommendations made by the forest engineer responsible for the allowable cut calculation.

2.2. Future climates

In the field of climate sciences, projection of climatic conditions into the future takes place as two distinct steps:

- the creation of climate scenarios and
- the modelling of future climate as a function of these climate scenarios.

2.2.1. Climate scenarios

In 2014, the Intergovernmental Panel on Climate Change (IPCC) published its fifth report on the future evolution of climates (AR5, IPCC 2014). In this report, the IPCC presents 5 possible future greenhouse gas (GHG) emission profiles. These GHG concentration projections (Figure 2), called representative concentration pathways, or RCP, are based on sets of assumptions about, for example, world population, economic activity, energy consumption, and the development and implementation of new technologies.

The effect of GHG concentration over time for the earth's energy balance is projected forward using numerical models. The intensity of this effect on global surface temperatures is expressed in terms of radiative forcing (in W/m^2). The greater the radiative forcing, the higher the mean annual temperature will be. These GHG projections are named as a function of the anticipated radiative forcing in 2100, the number in the scenario's name being the corresponding radiative forcing in W/m^2: RCP 2.6 (the lowest GHG concentrations), RCP 4.5, RCP 6.0, and RCP 8.5. Among the concentration pathways, this last scenario leads to the greatest global warming: an increase of mean annual global surface temperature between 2.6 and 4.8°C in 2100, depending on the climate model used.

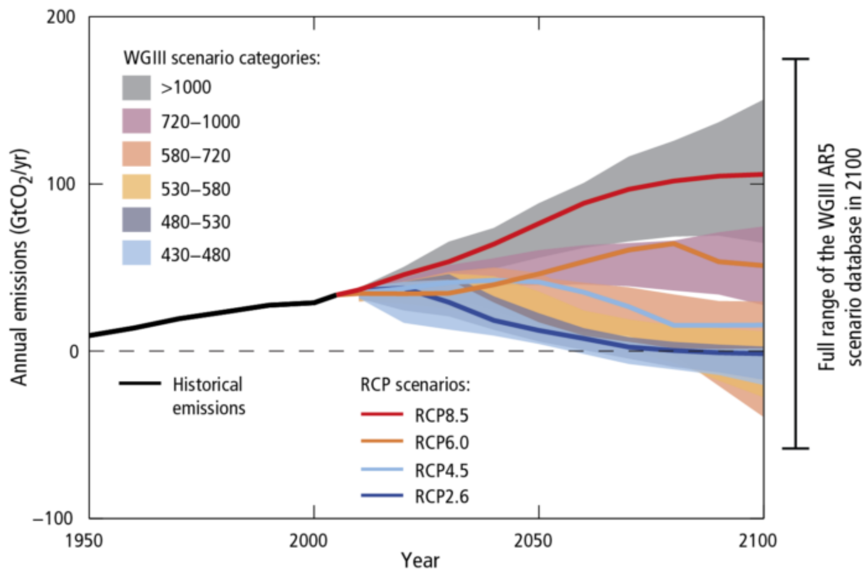


Figure 2. Illustration of historical CO_2 emissions and five representative concentration pathways to the year 2100[8].

2.2.2. Climate models

Based on the various concentration pathways, a number of research groups have modelled future climates. To do this, global circulation models (GCM) were constructed. These models simulate the state and behaviour of the atmosphere as influenced by atmospheric GHG concentrations, solar radiation, and characteristics of the earth's surface. Also, certain models, called "ocean-atmosphere" or "coupled" models, simulate the causal relationships that link oceans and the atmosphere. Finally, these coupled models are often combined with models that simulate the movement of chemical substances (e.g., CO_2) through the atmosphere; these models are called "Earth System Models" (ESM).

2.3. Processes of particular interest under climate change

According to the scientific literature, climate change is already affecting (Hogg and Bernier 2005, Lemmen et al. 2008, Williamson et al. 2009, Mitton and Ferrenberg 2012) and will further influence many components of forest ecosystems (Lindner et al. 2010, Gauthier et al. 2014, Scheffers et al. 2016). It is therefore possible to anticipate, based on the scientific literature, a broad range of impacts.

2.3.1. Forest fires

Forest fires play an important role in the boreal forest (Stocks et al. 2003, Gauthier et al. 2015). Fires influence the structure, age, and composition of forests and, through their effect on these, a broad range of forest ecosystem characteristics such as the availability of wood volume and wildlife habitat.

2.3.1.1. Forest fires and climate change

The influence of atmospheric conditions on forest fires is well documented (Flannigan and Wotton 2001). This influence is expressed at the time scale of the fire season (Van Wagner 1987), but also on longer time scales, such as that of climate (Flannigan and Wotton 2001, Girardin and Mudelsee 2008). For some time now, researchers have documented a linkage between human-induced climate change and an increase in the annual area burned (Gillett et al. 2004, Hanes et al. 2019). Over the recent decades, many authors have projected forward the effects of climate change on fire regimes (Stocks et al. 1998, Flannigan et al. 2005, Boulanger et al. 2014 and 2017, Gauthier et al. 2015).

[8] Illustration drawn from the AR5 report, IPCC 2014.

2.3.1.2. Fire modelling

There exist many types of fire models. Fires can be modelled in a spatially explicitly manner (Fall et al. 2004) or not (Boulanger et al. 2014). Fire modelling can be mechanistic: according to this approach, stand composition, topography, and wind speed, for example, can be used to calculate the speed of fire propagation and the intensity of a fire (Van Wagner 1987, Yamasaki et al. 2008, Tymstra et al. 2010). Fire modelling can also be empirically based (Fall et al. 2004, Boulanger et al. 2014). For this type of modelling, a statistical analysis of the relationships among area burned and factors influencing area burned (such as weather and the abundance of fuel types) serves as the basis for simulating burn areas by time period. The degree of complexity of models is also highly variable among models.

In order to better capture the spatial variability of fires at a large scale, certain authors have developed a zoning system. Within each zone, fire parameters are considered to be homogeneous (Boulanger et al. 2014 and 2017, Bouchard et al. 2015) and fires are modelled according to these zones.

2.3.1.3. Effect of forest composition on forest fires

The influence of forest composition on fire behaviour has been recognized for many years (Van Wagner, 1987). Recent work by Bernier et al. (2016) demonstrates how, at a pan-Canadian scale, forest composition (whether forests are mostly old or young and deciduous or conifer) influences the propensity of forest stands to burn. Based on these results, Bernier et al. (2016) calculate a fire risk adjustment factor as a function of forest landscape composition. This adjustment factor can thus be used to modulate projections of future fire regimes as a function of landscape scale forest composition.

2.3.2. Spruce budworm

Spruce budworm is one of the most important defoliators of coniferous stands in North America (MFFP 2016). During the course of outbreaks, spruce budworm defoliates a significant area of forest in Quebec, particularly in mature stands of balsam fir, white spruce and, to a lesser extent, black spruce (Bouchard et al. 2015). Indeed, during the course of the last outbreak (1967 to 1992), spruce budworm caused severe mortality in 4 million hectares of forest, and a loss of 180 million cubic meters of balsam fir volume in Quebec (MFFP 2016). Defoliation within a stand can vary from mild to severe, in part due to the age and species composition of the stand. When defoliation is sufficiently severe, it can lead to mortality among stems within a stand (Bouchard et al. 2015).

Climate change is expected to affect the pattern of spruce budworm outbreaks significantly (Régnière et al. 2012, 2019). More specifically, budworm is limited at the northern limit of its distribution by excessively cold temperatures, since the insect is not able to complete its life cycle under these conditions (Régnière et al. 2012). Its performance is also poorer in the southern part of its range, since excessively hot winter temperatures interfere with the onset of diapause and weaken the insect. (Han and Bauce, 1998). Based on an understanding of the physiology of spruce budworm, the area to be affected by budworm outbreaks is expected to migrate northward (Régnière et al. 2012).

2.3.3. Forest growth

Climate is an important determinant of the abundance and productivity of conifer and deciduous tree species. Climate change could significantly affect the degree of overlap between current and future tree species habitat (Périé and de Blois 2016). Indeed, recent research suggests that boreal forest tree productivity in Quebec could change under climate change, with increased growth in colder regions and decreased growth in warmer regions and where moisture deficits are more prevalent (D'Orangeville et al. 2018).

2.3.4. Regeneration failure

Certain tree species, like black spruce and jack pine, can store large quantities of propagules in their aerial seed bank (called serotiny); these propagules are then released by the passage of fire and dispersed by wind. High levels of seed production combined with the resistance to fire of jack pine seed cones and the clustering of cones of black spruce (Splawinski et al. 2019b) help to maintain stand densities and compositions that remain comparable after the passage of fire, thus allowing landscapes to self-regulate over time (Johnstone et al. 2010). However, when fire burns a stand before its trees have reached reproductive maturity, regeneration of the stand can fail since there is an insufficient quantity of viable propagules to ensure stand regeneration.

Many authors have studied regeneration failure that occurs after the passage of fire (Payette et al. 2000, Payette and Delwaide 2003, Côté and Gagnon 2002, Côté 2003 and 2004, Girard et al. 2008 and 2009). Splawinski et al. (2019a) have discussed how fire return interval, forest management, and the maturity of tree species influence the frequency of regeneration failure in the boreal forests of Quebec.

2.4. Structure and function of a modelling exercise

2.4.1. Structure of a simulation model

The structure of a simulation model – that is, the choice of components to include and how these components are made to interact – largely determines the types of questions that can be answered with the model. A model must therefore be sufficiently complex so as to include the required details and allow interaction among key processes, but no more. The principal of parsimony is very helpful in this context, since the simplest model structure that allows questions of interest to be answered is the one best suited to the task (Box, 1976).

In all modelled systems, certain processes occur at too fine a scale to justify inclusion in a model. This is the case when the effort required to include these “underlying” mechanisms (Figure 3) is too great as compared to the resulting increase in the model’s ability to answer questions. For example, the microbial decomposition of leaf litter is only rarely included in landscape scale models.

Conversely, other processes occur on too large a scale to be included in models. Such large scale processes can be considered as being part of a modelled system’s “context” (Figure 3). For example, from a systems perspective, climate provides context to forest ecosystems.

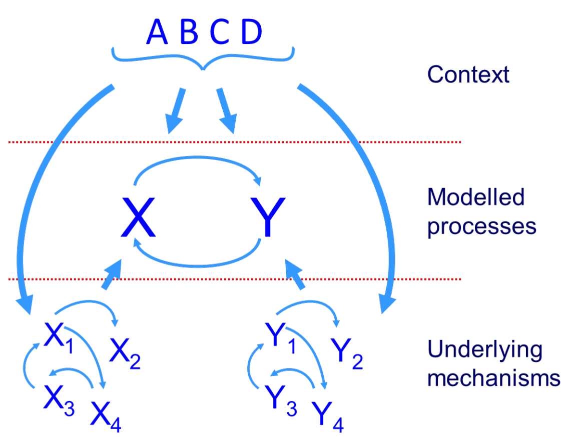


Figure 3. Illustration of a hierarchical organization of sub-systems and the linkages among “modelled processes” (for example, fire propagation), their context (for example, climate), and underlying processes (organic matter decomposition, for example).

Even when the integration of contexts or underlying mechanisms (Figure 3) is not desirable or possible, it may be necessary to take these mechanisms into account in order to properly model a system. In order to create linkages between higher or lower order mechanisms and the modelled system, two options are available: tight and loose coupling. Two models linked by tight coupling run at the same time and are linked dynamically; that is to say the information from one model can be piped into another model in real time. This type of coupling can engender a structural rigidity that may become difficult to manage over time. Conversely, two models are loosely coupled when context and underlying processes are modelled ahead of the principle modelling exercise (“modelled processes” in Figure 3) is run. The information that is communicated through loose coupling can be standardized to facilitate integration into other modelling processes.

2.4.2. Modelling interactions

Climate change is expected to have direct effects, such as the effect of increased moisture deficits on fire mean return intervals. Meanwhile, there is a potential for a very large number of indirect effects of climate change on the forest, such as a contraction of caribou habitat that results from a reduction in the mean age of forest landscapes. These interactions among the many components of forested ecosystems can create emergent properties, which are model behaviours that result from the interaction of many modelled ecosystem components.

In order to provide as complete a picture as possible of the potential impacts of climate change, a model must therefore be capable of capturing direct effects within ecosystems, but also indirect effects and emergent properties.

2.5. Uncertainty

In natural systems, there are a great many sources of uncertainty: climate and natural disturbances are but two examples. These sources of uncertainty – the result of an incomplete understanding, stochastic behaviour, or both – contribute to the challenges of forest management. In the past, very few sources of uncertainty are integrated into forest management planning, and this has been the case since the very first formalizations of forest management. However, many authors have underlined the importance of integrating uncertainty into decision-making in a context of forest management (Thompson 1968, Weintraub and Abramovich 1995, Yousefpour et al. 2012). Uncertainty becomes increasingly important in a context of strategic forest management when ecosystems are dominated by natural disturbance, such as in the boreal forest, because the long term performance of management strategies is strongly affected by these different sources of uncertainty.

2.6. Decision support

In the context of a process generating a significant amount of important information, a participating decision-maker requires support in order to identify the elements that must be considered during the decision-making process.

Indeed, this project seeks to compare adaptation measures based on a number of indicators, which constitutes a conventional decision-making context. However, the situation is made more complex by the uncertainties associated with climate scenarios and models, as well as the uncertainties related to the behaviour of forests in the face of evolving conditions. Furthermore, the establishment of management guidelines based on current conditions and an observation of historical patterns poses challenges for the decision-maker who wishes to develop a vision for the future as well as actions over the short, medium, and long term. The temporal dimension thus becomes an integral part of the decision-making process. Finally, a decision-maker will need to express values and sensitivity to risk that are based on perceptions and preferences.

Such a complex decision-making context cannot be addressed with conventional means (Roy 1992). In such a context, decision-support science may be helpful in transforming modelling results into knowledge, and then into information that can support decision making.

Developed over the past 50 years, decision support has been applied to the resolution of such complex situations. This approach is especially well suited when many decision-makers, each holding distinct preferences, are involved. The multiple dimensions of the current project justify the use of decision-support in this context.

Indeed, sustainable forest management is defined as management that “seeks to maintain or improve the long-term health of forest ecosystems, in order to provide current and future generations with environmental, economic, and social benefits from these ecosystems” (MFFP 2020). As well as ensuring economic efficiency, social equity, and environmental integrity, the decision-making process should take into consideration the proximate and future consequences of decisions on a time horizon that corresponds to the time required for ecosystems to regenerate. This process should then seek to balance, over many time horizons, the preservation of biological diversity, the maintenance of forest ecosystems, the maintenance of multiple socio-economic benefits, and values expressed by the public. Second, the decision-making process should ideally involve a sharing of visions for the future because the process brings together many interested parties with different and possibly opposing values and points of view. Third, the consequences of management options should be evaluated over the short, medium, and long term. Also, many uncontrollable events (such as forest fires or insect outbreaks) could occur once the planning process has concluded, making forward projections inaccurate. The problem is then of a temporal nature, evolving in a context of uncertainty.

Multi-criteria decision support is a field of study in its own right (Urli 2013). It is based on operational research and other disciplines such as psychology, sociology, economics and computer science (Martel, 1999). It is a structured process that helps inform decision-making in contexts involving complexity, such as the context of this project. Decision support is called multi-criteria when decisions cannot be taken based on one single criterion.

Multi-criteria decision support has been described as a highly practical tool for forest management as it provides a formal framework for decision-making (Mendoza and Prabhu 2003, Munda 2004, Kangas and Pukkala 1992). It allows many economic, environmental, or social criteria to be taken into account, without requiring that the criteria be aggregated onto one common scale (Bertrand 2001). The objective of multi-criteria decision support is to identify the best possible compromise solution by taking into account all criteria. There is, in general, no optimal solution over all criteria simultaneously, given the often conflicting nature of decision criteria.

Multi-criteria decision support is therefore not a planning approach where information is collected and processed so as to impose a purportedly optimal solution on the decision-maker. Rather, the process should be structured and constructive, and aim to provide tools to move forward the resolution of complex decision problems (Vincke 1989).

Multi-criteria decision support consists of comparing different actions (projects, plans, strategies, variants, programs, options, and measures) on the basis of several criteria (indicators or attributes) defined by the decision-maker. The decision-maker should also determine personal preferences in terms of the weight assigned to each criterion, as well as threshold values for preference, indifference, and veto. Potential future actions are then evaluated according to each criterion to form a performance evaluation matrix (Vincke 1989). Although not strictly necessary, a multi-criteria aggregation procedure can be used. The complexity of the problem may make the application of an aggregation method advantageous; a method appropriate to the situation may need to be developed if one does not already exist.

3. Methodology

The information and methods used in the project are presented in the following sections. The model developed for project is called BFEC-CC (for “Bureau du Forestier en chef – changements climatiques”).

3.1. Study area and data pertaining to forests

3.1.1. Description of the study area

A study region was selected to test the approach and model developed in the context of this project. The project team focused on the Saguenay – Lac-Saint-Jean region, located in the heart of the Quebec boreal forest (Figure 4). The region was chosen because of the concurrence of many forestry related issues, notably: the significance of forests from a social and economic perspective, the broad range of uses, and the region's vulnerability to climate change. Indeed, recent research suggests that the region will likely be strongly affected by climate change (Gauthier et al. 2015). In addition, forest managers in the region are aware of climate issues and are already considering possible adaptation measures (Saguenay – Lac-Saint-Jean Forest Management Directorate 2018).

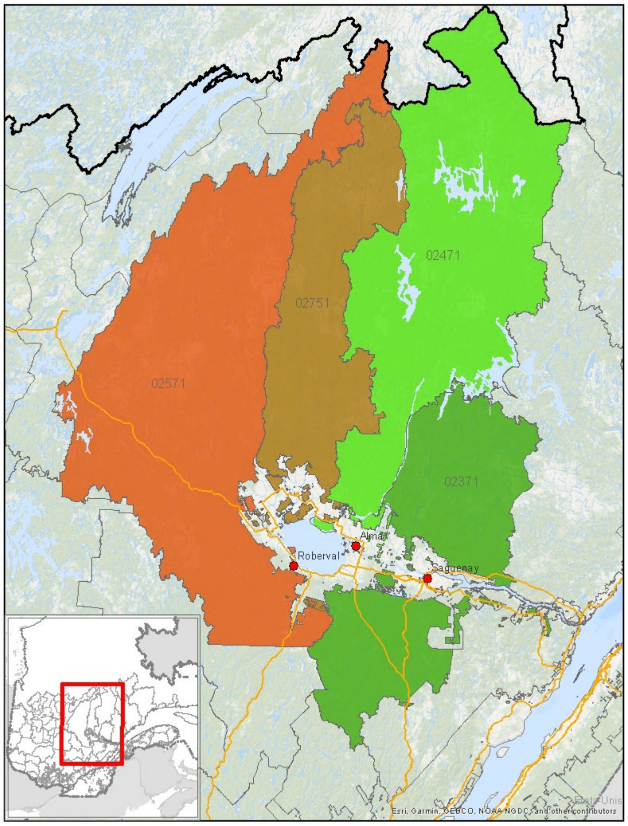


Figure 4. Location of the study area, in the Saguenay – Lac-Saint-Jean area.

The Saguenay – Lac-Saint-Jean region covers a vast area from the Laurentians Wildlife Reserve[9] in the south to the northern limit of managed forests in the north. Figure 4 shows the location of the region and the four management units it contains: 023-71, 024-71, 025-71, and 027-51. Forested area for the region covers more than 68,076 square kilometers, of which 60,703 square kilometers are managed. Forested area for each management unit is presented in Table 1. From north to south, the region covers three bioclimatic domains: the spruce-moss, fir-white birch, and fir-yellow birch domains. The natural disturbance regime is characterized by fires and outbreaks of the spruce budworm.

Table 1. Productive and managed forest area in the management units of the study area.

Management unit	Productive forest area (ha)	Managed area (ha)
023-71	1 257 060	1 115 923
024-71	1 885 503	1 615 100
025-71	2 630 737	2 428 822
027-51	1 034 352	910 500
Total	6 807 652	6 070 345

The Saguenay – Lac-Saint-Jean region is important from a forestry perspective; the region has the highest annual allowable cut of any region in Quebec. There are 32 wood supply licensees who, among them, share over five million cubic meters of wood annually. In 2013, forest harvesting was the forest industry sector employing the most people (2,388) in the region, followed closely by the primary processing industry (2,304). Finally, there were 1,306 people employed by secondary and tertiary processing industries (Saguenay – Lac-Saint-Jean Forest

[9] TN: « Réserve faunique des Laurentides » in French.

Management Directorate 2018). More than 400 companies are listed in the forestry sector, which generate approximately $ 1.9 billion in sales annually (Saguenay – Lac-Saint-Jean Forest Management Directorate 2018).

Since the year 2000, allowable cut in the region has dropped 24%. This decrease is attributable to a number of factors. Following the Coulombe Commission in 2005, the allowable cut of the Fir-Spruce-Pine-Larch group was decreased by 20%. Since the creation of the Office of the Chief Forester, the calculation and determination of allowable cuts have incorporated several new constraints, notably for the implementation of ecosystem-based management. These elements contributed to the decline (Saguenay – Lac-Saint-Jean Forest Management Directorate 2018).

Access to the region's forests is important for the region given the number and diversity of stakeholders present. Several Aboriginal communities are present on the landscape in addition to recreational users, hunters, trappers and other users of the forest. Certain areas within the region are assigned administrative protections; for example, woodland caribou protections occupy a significant portion of the region. The harmonization of uses and land protections are important and influence forest management. These elements are taken into account in operational and tactical planning, but also at the strategic level in the calculation of annual allowable cuts. Table 2 shows annual allowable cuts determined for the 2018-2023 period for the Saguenay – Lac-Saint-Jean region. The allowable cut in effect, as gross merchantable wood volume, is equal to 7,216,700 m^3 per year.

Table 2. Annual allowable cut levels for the Saguenay – Lac-Saint-Jean region

Management unit	2018-2023 annual allowable cut, as gross merchantable volume (m^3/year)									
	Fir, Spruce, Pine, Larch	Cedar	Hemlock	White and red pine	Poplar	White birch	Yellow birch	Sugar and red maple	Other hardwoods	Total
023-71	1 160 700	200	0	900	141 600	186 500	37 600	9 200	900	1 537 600
024-71	1 307 200	0	0	400	49 200	172 100	10 100	3 600	0	1 542 600
025-71	2 398 400	0	0	0	337 800	323 900	4 600	4 900	100	3 069 700
027-51	881 400	0	0	100	73 500	108 900	1 200	1 500	200	1 066 800
Total	**5 747 700**	**200**	**0**	**1 400**	**602 100**	**791 400**	**53 500**	**19 200**	**1 200**	**7 216 700**

3.1.2. Management strategy

The regional forest management strategy that is applied to modeling in the context of this project has been simplified for the purposes of the study from its full specification in the annual allowable cut determination process. Three treatments were retained: clearcutting, pre-commercial thinning, and tree planting. Salvage cutting, a variant of clearcutting, is also available when wood volume must be recovered after a fire. The retention of residual stems, as individual trees or groups of trees in clear-cuts, is equal to 2% of merchantable timber. The area targets for the pre-commercial thinning and plantation treatments were taken from the regional strategy. Annual targets were thus set for 20,086 hectares of plantation and 3,936 hectares of pre-commercial thinning, distributed among the four management units of the region.

The maintenance of an age class structure that approximates natural landscapes is integrated into the calculation of annual allowable cuts as a constraint. The objective is to "... maintain a forest whose age structure is within the limits of natural variability" (Bureau du forestier en chef 2018b). The method used in the project to calculate the proportion of old forest are based on the methods applied by the Chief Forester for the annual allowable cut calculations (Bureau du forestier en chef 2018b). Old forest threshold values are applied at the territorial analysis unit[10] scale.

[10] TN: "Unité territoriale d'analyse" in French.

3.1.3. Management strata and their evolution

In the context of annual allowable cut calculations, management strata are groupings of forest stands of similar characteristics (Bureau du forestier en chef, 2018b). Clustering to obtain management strata for this project was done on the basis of three criteria: (i) the silvicultural scenarios for which each stratum is eligible, (ii) the physical environment (potential vegetation[11] was used as a proxy for physical environment type), and (iii) stand type (see below for an explanation of stand type). The first two criteria were used to group stands according to all possible combinations of silvicultural scenarios and physical environments.

Stands were further grouped according to stand type, here taken as the relative amounts of merchantable volume by species group. Species groups for this project include: balsam fir [SAB], shade-intolerant deciduous [Fi], shade-tolerant deciduous [Ft], shade-intolerant conifer [Ri] and shade-tolerant conifer [Rt]. To achieve groupings by stand type, yield curves for each silvicultural scenario by physical environment were further partitioned into low, medium, and high yield strata by applying quantile regression to all yield curves within a grouping. This final partitioning into three yield classes led to the creation of the project's management strata. The source yield curves were originally created for the region's annual allowable cut calculation (Bureau du forestier en chef, 2018a) and volume data were generated by the Natura forest growth model (Auger 2017). It should be noted that the yield curves generated for this project implicitly take into account any lags in regeneration time. In the study region, these lags are mainly due to the presence of ericaceous shrubs.

Since there is only one yield curve associated to each forest stratum, the effect of silvicultural treatments (section 3.1.2) is implemented in the BFEC-CC model as a transition to a different stratum. For each management stratum, the post-treatment yield curve is obtained as a weighted average of the post-treatment yield curves generated for the allowable cuts calculations in the region (Chief Forester's Office, 2018a). Weighting is based on the surface area associated to each curve. Allowable cut calculation models for the region included over 3,600 management strata. The process described herein made it possible to reduce the number of management strata to 207.

3.1.4. Data included in the BFEC-CC model

Much data were included in the BFEC-CC model. The types of data and their sources are presented in Table 3.

Table 3. Tabular data included in the BFEC-CC model, and the sources for each type of data

Data	Source
Merchantable deciduous and conifer volume by strata	From the grouping of stand into strata, presented in section 3.1.3.
Transitions following an action in the model	Based on the transitions after management actions, as implemented in the allowable cut calculation (section 3.1.3).
Maximum area as pre-commercial thinning	From targets specified by management unit, as included in the management strategy for the allowable cut calculation
Maximum area as plantation	From targets specified by management unit, as included in the management strategy for the allowable cut calculation
Minimum area to maintain as old forest, by territorial analysis unit	From targets specified by territorial analysis unit, as included in the management strategy for the allowable cut calculation
Age of eligibility for harvesting, by strata	From the yield curves (see section 3.1.3)

[11] TN: “Végétation potentielle” in French.

Spatial inputs for the model were included as GeoTiff rasters. This data was created from vector layers used for the allowable cut calculations, and were transformed into raster format at a scale of 14.44 hectares. The following list shows the different raster layers generated for the model:

- Management units
- Area as managed forest
- Area as unmanaged forest
- Non forested area, by type
- Stand age
- Initial management strata
- Presence of roads, by type
- Bioclimatic sub-domain[12]
- Territorial analysis units.

3.2. Modelling climate change

3.2.1. Climate information

In the context of this project, three climate scenarios (section 2.2.1) and climate data from three earth system models (ESM, section 2.2.2) were included.

The RCP scenarios included in the project are the following:

- Historical : the baseline climate, for the period 1980-2010
- RCP 4.5: a moderate climate change scenario, corresponding to an increase in mean annual temperature of 1.6 to 4.2 °C for the Saguenay – Lac-Saint-Jean for the period 2071-2100[13]
- RCP 8.5: a more intense climate change scenario, corresponding to an increase in mean annual temperature of 3.8 to 7.1°C for the Saguenay – Lac-Saint-Jean for the period 2071-2100[13].

In the context of this project, 2071 to 2100 climatic conditions are maintained to the end of simulation, in 2170. This use of climate data was necessary because the simulation period for annual allowable cut calculation (150 years) is longer than the period for which climate data is available (80 years, from 2020 to 2100).

Climate data for the project were generated by three earth system models (ESM):

- CanESM2: Canadian Earth System Model, version 2
- MIROC-ESM-CHEM: Model for Interdisciplinary Research – Earth System Model
- HadGEM2-ES: Hadley Global Environment Model 2 - Earth System.

The historical climate data for the project were obtained from outputs of the CanESM2 model; this was done to ensure a high degree of compatibility with the climate change data. To maintain consistency among the different processes modeled under climate change, the same combinations of climate scenarios and ESM (Table 4) were applied to:

- The updated fire simulations based on Boulanger et al. (2017) and provided by the author (2.3.1)
- The simulation of forest stand productivity (Power et Auger, 2019; see section 2.3.3)
- The mean annual temperature data applied to the spruce budworm process (section 2.3.2).

[12] TN: "Sous-domaine bioclimatique" in French; for details, see https://mffp.gouv.qc.ca/forets/inventaire/inventaire-zones-carte.jsp
[13] https://www.ouranos.ca/portraits-climatiques/#/regions/30.

Table 4. ESM and climate scenario (RCP) combinations applied in the context of this project.

Climate scenario	Climate models (ESM)		
	CanESM2	MIROC-ESM-CHEM	HadGEM2-ES
Historical	☑		
RCP 4.5	☑	☑	☑
RCP 8.5	☑	☑	☑

3.2.2. Structure of the modelling framework

The modeling tool used for the project is SELES (Fall and Fall 2001). This tool allows the integration of stochastic processes and the tracking of spatial information in raster format. Since there are no boundaries in raster data, as is the case with polygon data, the model can more easily apply new disturbances. The time step applied to the modeling is one year.

In the modelling framework developed for the project, climate is considered to be a part of the model's context (Figure 3), and therefore no climate process is explicitly modeled within the BFEC-CC model.

Two processes are considered to be underlying the processes modelled by BFEC-CC (Figure 3) and are integrated into the framework as inputs to BFEC-CC:

1) The effect of climate on forest productivity: the effects of climate on forest productivity were integrated through the inclusion of the outputs of a stand level model, developed in a parallel project (Power and Auger 2019; section 2.3.3),
2) The effect of climate on forest fires: the modelling results drawn from Boulanger et al. (2014 and 2017) were included as BFEC-CC inputs (section 2.3.1).

These BFEC-CC inputs were produced by models that are external to the project, thus establishing loose coupling between these external models and BFEC-CC (section 2.4.1).

3.2.3. The integration of uncertainty

There are a great many sources of uncertainty in the natural world (section 2.5). Of these potential sources of uncertainty, only the uncertainty related to climate (i.e., the three RCP scenarios and three ESM) were integrated into the project, although it would have been possible to integrate a greater number of sources. It was therefore necessary to take into account climate-related uncertainty in the analysis and presentation of results for decision support (section 3.3.2).

3.2.4. Modelled processes

The different processes modelled by the BFEC-CC landscape model are presented in Table 5. Key processes are described in subsequent sub-sections.

Table 5. Modelled processes, the areas to which the processes are applied, and their main effects.

Order of execution	Module	Area of application	Main effects
1	Fire	Forested land	Stand initiating disturbance
2	Severe mortality due to spruce budworm	Forested land	Stand initiating disturbance
3	Caribou habitat	Entire region	Update to disturbed area and inventory of habitat
4	Availability of forested land to management	Managed forest	Evaluation of management constraints
5	Evaluation of growing stock	Forested land	Updates to merchantable volumes; effects of climate change on volumes; calculation of harvest target
6	Salvage logging	Managed forest containing salvageable volume	Salvage of burnt timber
7	Green wood harvesting	Managed forest eligible for harvesting	Harvesting by clear cut
8	Regeneration	Disturbed forested land	Natural regeneration and evaluation of eligibilities for planting and other treatments
9	Tree planting	Managed forest eligible for planting	Decision to plant; assignment to new (post-disturbance) strata; eligibilities to other treatments
10	Intensive management zones	Designated intensive management zones	Tree planting in intensive management zones
11	Pre-commercial thinning	Managed forest eligible for pre-commercial thinning	Pre-commercial thinning; assignment to new (post-disturbance) strata
12	Road management	Entire region	Activate / deactivate roads as a function of time since harvest in adjacent stands
13	Natural succession	Forested land	Increase age by time step

3.2.4.1. Forest fires

Depending on the model used, the impact of wildfire in the boreal forest will likely increase because of climate change effects (section 2.3.1.1). It was therefore essential that this phenomenon be included in the model. The behavior of forest fires is presented in the following sections.

Fire initiation

Historically, the distribution of forest fires within the study area is not uniform. Indeed, the distribution of area burned in the region between 1920 and 2017 shows a concentration of fires at the northern and western extremities of the study area. To create a probability surface that conditions fire initiation in the BFEC-CC model that is based on fire history, a moving window with a radius of 100 kilometers was superimposed over every raster cell of the fire frequency map. For each cell, the sum of fire occurrence within the moving window was written to the corresponding cell on the newly created fire probability map. Thus, a smoothed fire history surface was created and included in the model to inform the initiation of fires (Figure 5). Fires can only be initiated in forested raster cells that have not been disturbed in the current year.

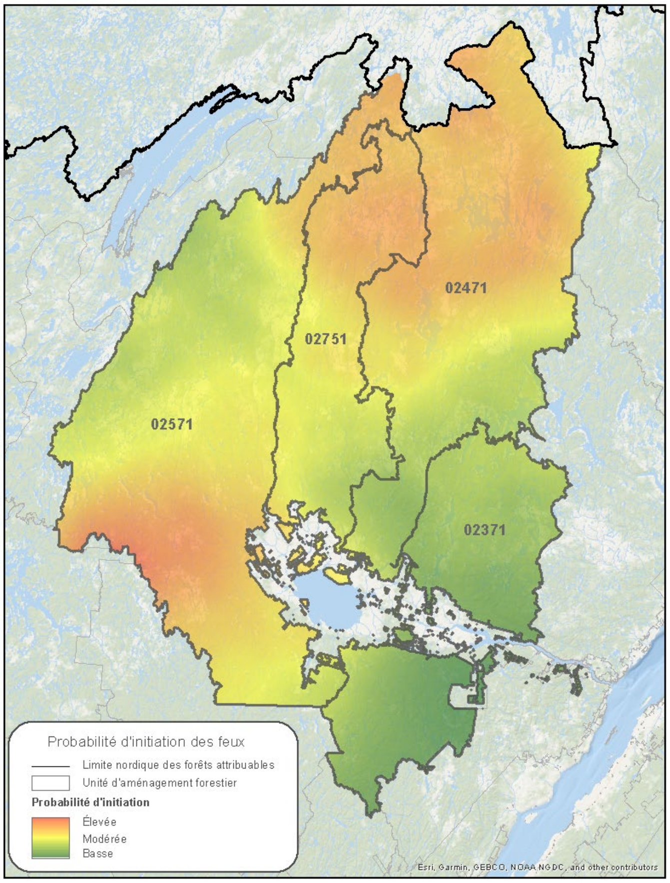


Figure 5. Probability of initiation of wildfires over the region.

Area burned

The area to be burned annually by the model under the different climate scenarios was provided by the Canadian Forest Service (Boulanger, pers. comm.). This area to be burned annually was estimated using the modeling tool described by Boulanger et al. (2014 and 2017) updated by the first author, while applying the same climate data as used in this project (section 3.2.1). The study area falls entirely within the Homogenous Fire Regime (HFR) Eastern James Bay zone (Boulanger et al. 2013), with the exception of a few hectares at the eastern end of the region. The fire data for this HFR zone were therefore used for the entire study area, the Saguenay – Lac-Saint-Jean region.

Fire data were applied by 30 year period (2011-2040, 2041-2070, 2071-2100). After 2100, conditions are assumed to be equivalent to 2071-2100. To complete the time series of future fires, the period 2071-2100 was sampled as often as necessary to complete the time series (i.e., up to 2170). One hundred fire regime replicates were provided, but only the median replicate, the replicate burning the median area (average over the length of the fire record), by climate scenario and ESM, was applied in the context of the project.

As described in the appendices of Bernier et al. (2016), the effect of forest composition on the annual burn rate was removed from Boulanger's area to be burned annually data by applying a correction factor of 1.64 (Boulanger et al. 2017). The effect of forest composition on area to burn is then reintroduced into the fire data by the model at each time step (section 2.3.1.3).

Fire events

The extents of individual fire events are drawn from the Canadian National Fire Database (CNFDB)[14]. In order to reproduce the size distribution of historical fires for the region, only historical fires within the region were included. Two hundred and fifty fire size sequences were constructed by randomly sampling the history of fire sizes for the region (a sample of data is provided in Table 6). These fire events are read by the model during a simulation year, sequentially, until the target area to be burned annually is reached.

Table 6. Extents (in hectares) of individual fire events (showing only the top 20 rows of 250) for the first 10 replicates (columns) of fire size sequences for the region.

Index	r1	r2	r3	r4	r5	r6	r7	r8	r9	r10
1	3045	23673	1657	15701	11312	2270	68426	11312	9858	6585
2	47581	1762	2514	2270	2359	68426	368	47581	368	1389
3	1657	23198	68426	2359	1762	15701	2270	9858	6585	322
4	9858	68426	2514	2514	2075	961	1762	1670	368	287
5	755	9858	2359	368	1670	47581	3045	68426	6585	47581
6	755	15701	368	2514	3109	1657	4165	2359	1670	1657
7	322	3109	473	2359	961	3109	23198	3045	68426	3045
8	4165	1389	473	15701	1670	1670	473	11312	23673	322
9	1762	287	1762	2514	322	47581	6585	2359	2270	6585
10	473	68426	961	1670	1657	3045	68426	11312	755	961
11	1670	287	3109	6585	1657	473	473	23673	23198	23673
12	9858	15701	23198	4165	15701	23198	755	1762	287	2359
13	47581	68426	6585	2514	15701	1762	47581	9858	2514	3045
14	2075	11312	23673	368	68426	1389	287	6585	23673	47581
15	1657	961	23673	368	23673	473	1762	287	1762	2075
16	368	9858	11312	1657	375	2075	375	322	4165	4165
17	2359	6585	2075	473	6585	322	47581	1389	11312	1389
18	2359	2075	3045	2270	1389	47581	375	473	1389	68426
19	1389	375	47581	68426	375	11312	961	3045	11312	23198
20	961	1389	6585	4165	2359	23673	68426	322	6585	2270

[14] https://cwfis.cfs.nrcan.gc.ca/ha/nfdb

Correction of burn rate with forest composition

To correct the area to be burned annually based on the composition of the forest over time, the correction described in the supplemental materials of Bernier et al. (2016) is applied by the model. Thus, at each time step, the model calculates a correction factor for the region's forest, and this factor is then applied to the area to be burned for that year. Burn rates having been corrected as per Bernier et al. (2016), the younger and more deciduous the landscape, the lower the burn rate. Conversely, the more the forest is made up of old and coniferous stands, the higher the resultant burn rate will be.

Table 7. Fire selection ratios used to calculate, as a function of forest composition, the correction factor on area to burn annually with the method of Bernier et al. (2016)

Selection ratio	Age class (years)		
	0-30	31-90	91+
Conifer	0.8	2	2.9
Conifer mixed	0.43	1.16	1.79
Deciduous mixed	0.22	0.57	0.96
Deciduous	0.15	0.4	0.63

The method of Bernier et al. (2016) was modified to better take into account the area regenerating after disturbance and where regeneration failed. In the work of Bernier et al. (2016), only three age groups are used (0-30, 31-90 and 91 years and over (Table 7). The work of Erni et al. (2018) was used to create more resolution in the selection ratios for young stands, in the 0-30 year age class (Table 8). The 0-30 year age class was thus subdivided into 5 selection ratios, and these ratios were defined so as to maintain a good correspondence with the classes of Bernier et al. (2016). For example, the values for classes 31-90 and 91 and above have not been modified. Also, the mean values of the newly-defined selection ratios for classes from 0 to 30 years, weighted by the number of years to which they apply, closely match the values proposed by Bernier et al. (2016) for the same range of ages by composition class (conifer, conifer mixed, deciduous mixed, or deciduous).

Table 8. Fire selection ratios updated for the project. A new age class of 0 was included to better take into account area where regeneration failed when correcting annual area to burn in the BFEC-CC model.

Selection ratios	Age classes (years)						
	0	1-5	6-10	11-15	16-30	31-90	91+
Conifer	0	0.1	0.63	0.9	1.1	2	2.9
Conifer mixed	0	0.05	0.25	0.4	0.65	1.16	1.79
Deciduous mixed	0	0.02	0.1	0.2	0.34	0.57	0.96
Deciduous	0	0.01	0.07	0.13	0.25	0.4	0.63

Fire spread

The spread of fire from a burning cell to its neighboring cells (Figure 6) is subject to a number of constraints. For a fire to propagate to a cell, that cell must be forested and must not have been disturbed in the current time step (e.g., a fire cannot burn the same cell twice in the same year). Also, when fire propagates, the number of cells to which the fire can spread is drawn from a normal distribution having a mean of 1 and a standard deviation of 0.3. This number of recipient cells must be between 1 and 6. These propagation parameters, which in no way influence the area burned, were determined so as to create complexity in the contours of fire events. Having determined the number of recipient cells, the model determines the probability of spreading to each neighboring cell based on the composition and age of cells using the updated selection ratios (Table 8) of Bernier et al. (2016).

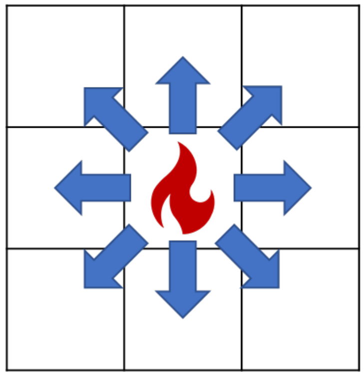


Figure 6. Illustration of a burning cell, in the center of the diagram, attempting to spread to its eight neighbours.

When the area to burn target for the time step is reached, all fire spread in the model stops. In this way, the area to burn annually is never exceeded.

The effect of fire on forests

In the real world, the effect of fires on forests is quite complex, modifying a large number of characteristics, such organic layer depth, the abundance of propagules, and the amount of salvageable wood volume. In the context of the BFEC-CC model, the effect of fires has been greatly simplified: the main effect of fires is to reset stand age to zero, killing off living trees.

Salvageable wood volume is also evaluated when forested cells burn. The assumption made is that, if the stand is less than 50 years old at the time of the fire, no wood volume is recoverable after fire. For stands 50 to 80 years old, 50% of the merchantable volume before fire is salvageable. This proportion rises to 70% for stands older than 80 years. This recoverable volume drops to zero at the end of the second year after the passage of fire, due to the degradation of wood by xylophagous insects and the drying out of sapwood (Nappi et al. 2011).

Following the passage of fire, the model evaluates the regeneration potential of burned cells (section 3.2.4.4). If no regeneration failure occurs, burned cells transition according to the transitions specified for clear-cut stands in the management strategy (section 3.1.2).

3.2.4.2. Spruce budworm

The spruce budworm module is based on the methodology presented in Bouchard et al. (2015) and also on recommendations made by the first author on (i) the effects of climate change on the insect and (ii) adaptation of the methodology for the purposes of the project.

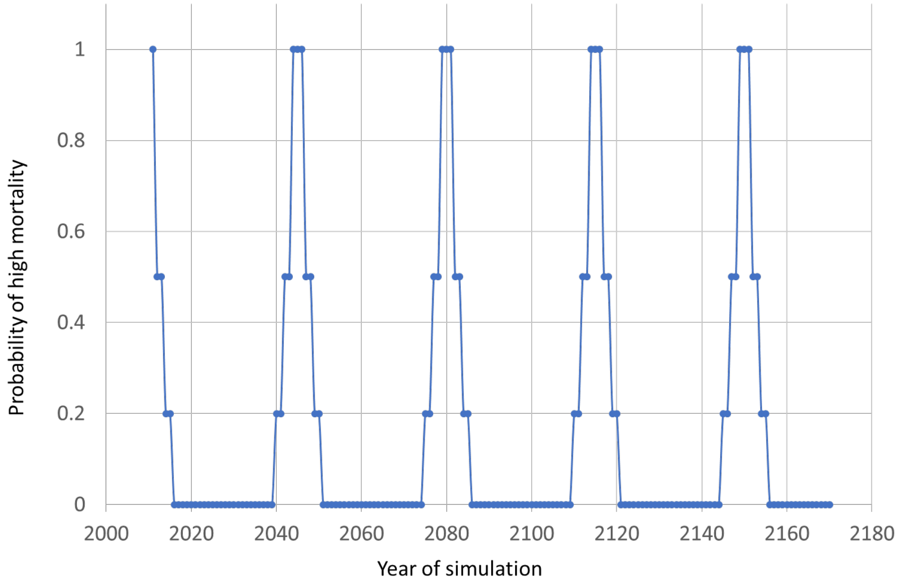


Figure 7. Probability of high mortality resulting from the intensity of the spruce budworm outbreak at a regional scale.

The spruce budworm module evaluates the probability that spruce budworm will cause severe tree mortality within forested cells based on the following characteristics:

- Stand species composition (Table 9)
- Stand age (Table 10)
- The intensity of the spruce budworm outbreak at a Provincial scale (Figure 7), and
- The mean annual temperature for the year of simulation.

To achieve this, the model multiplies the probabilities associated with each of these characteristics (all between 0 and 1), and compares this probability to a value between 0 and 1 drawn randomly from a uniform distribution. If the calculated probability is larger than the randomly drawn value, then high mortality is presumed to occur within the cell. Thus, if one of the four probabilities is equal to zero, then high mortality cannot occur. Conversely, if all characteristics are favorable to defoliation by budworm, the likelihood of defoliation is then very high.

For the modeling in the context of this project, the interval between budworm outbreaks is 35 years (Figure 7). The probability of high mortality within a cell as a function of the intensity of the Provincial budworm outbreak varies between 0 and 1 (Figure 7). The probabilities associated with stand age and composition are presented in Table 9 and in Table 10, respectively. In this context, the species (or group of species) identified as dominant (Table 10) is the species with the most abundant merchantable volume within the stand. The probabilities associated with different ranges of mean annual temperatures are presented in Table 11. Mean annual temperatures by territorial analysis unit are read from input files, as a function of the climate scenario and ESM in effect during a given simulation (section 3.2.1). These time series of annual mean temperatures were downloaded from the Ouranos data portal in NetCDF format for the centroids of each territorial analysis unit within the region.

Table 9. Probability of high mortality as a function of stand age

Age class	Probability of high mortality
0 to 30 years	0
31 to 60 years	0.5
More than 60 years	1

Table 10. Probability of high mortality as a function of the species, or group of species that dominate the stand

Composition	Probability of high mortality
Balsam fir	0.5
Black spruce	0.2
Jack pine	0
Tolerant hardwoods	0
Tolerant hardwoods	0

Table 11. Probability of high mortality due to budworm defoliation as a function of mean annual temperature

Lower bound (°C)	Upper bound (°C)	Probability associated with mean temperature
-273	-1	0
-1	0	0.5
0	2	1
2	3	0.5
3	∞	0

3.2.4.3. Forest growth

Power and Auger (2019) modified the Artémis-2014 stand-scale simulation model (Power 2016) to allow climate to influence the evolution of merchantable volume in the project's forest strata (section 3.1.3). This updated model simulates diameter increments, stem mortality, and stem recruitment over a wide range of potential vegetation (MFFP, 2015). The climate sensitivity of the Power and Auger (2019) model is the result of (i) an integration of the D'Orangeville et al. (2018) forest growth model, which simulates the basal area incremental growth of many species as a function of temperature and precipitation and (ii) the use of temperature and precipitation in the prediction of mortality for certain potential vegetation types.

With this updated climate-sensitive model, Power and Auger (2019) simulated the evolution of the region's sample plots over 150 years under a historical climate, and then under the different combinations of climate scenarios and ESM (Table 4). Since the stage of development of a stand influences how it responds to climate change, simulations were set up to simulate the different stages of development for all climatic periods (2011-2040, 2041-2070 and 2071-2100). These simulations thus integrate the effect of climate on stands established from 1930 (aged 90 years in 2020) to 2110 (stands established by the model during the simulation). After 2100, climatic conditions are considered to be constant.

Correction factors for merchantable volume under the different climate change scenarios were then calculated for each species group (Ri, Rt, Fi, Ft, and SAB) within each management stratum, and for every 20-year establishment period and 5-year stand age classes. Each correction factor was calculated as the ratio between merchantable volumes under each of the climate change RCP-ESM combinations and under a historical climate. These climate change volume correction factors are greater than 1 when merchantable volume is greater under climate change than under a historical climate, and less than 1 when volumes are lower under climate change. These correction factors were transferred to the BFEC-CC model as inputs to the model (the two models are therefore linked by loose coupling; section 2.4.1).

3.2.4.4. Regeneration of disturbed stands

Following a stand-replacing disturbance, for example fire or clear-cut harvesting, the BFEC-CC model evaluates how each forested cell will regenerate. The method applied to evaluate regeneration within the model is based largely on Splawinski et al. (2019a).

A diagram illustrating the evaluation of regeneration in the BFEC-CC model is shown in Figure 8. Following clear-cut harvesting and high mortality due to budworm defoliation, disturbed stands are regenerated according to the transitions specified in the allowable cut calculation; these stands are therefore always regenerated. Following a fire, if the stand is not dominated by jack pine or black spruce, the stand is always regenerated in the same stratum as before the disturbance. For stands dominated by jack pine or black spruce, the rules in Splawinski et al. (2019a) apply. Based on an original disturbance within these stands, the model determines whether the stand had reached reproductive maturity during the disturbance and therefore whether it is able to regenerate from seed. The values for age at maturity used are 30 years for jack pine and 50 years for black spruce. When the stand has not reached the age of maturity at the time of the disturbance and there is no significant hardwood component in the stand (i.e. at least 25% of the merchantable volume of species deciduous), then the stand fails to regenerate. On the other hand, if there is a significant hardwood component in the stand and the conifer component cannot regenerate, then the stand regenerates into a predominantly hardwood stand. To this end, three predominantly leafy strata have been identified, each of which corresponds to specific soil conditions. This correspondence was obtained by analyzing the frequency of occurrence of deciduous stands by type of potential vegetation (MFFP, 2015).

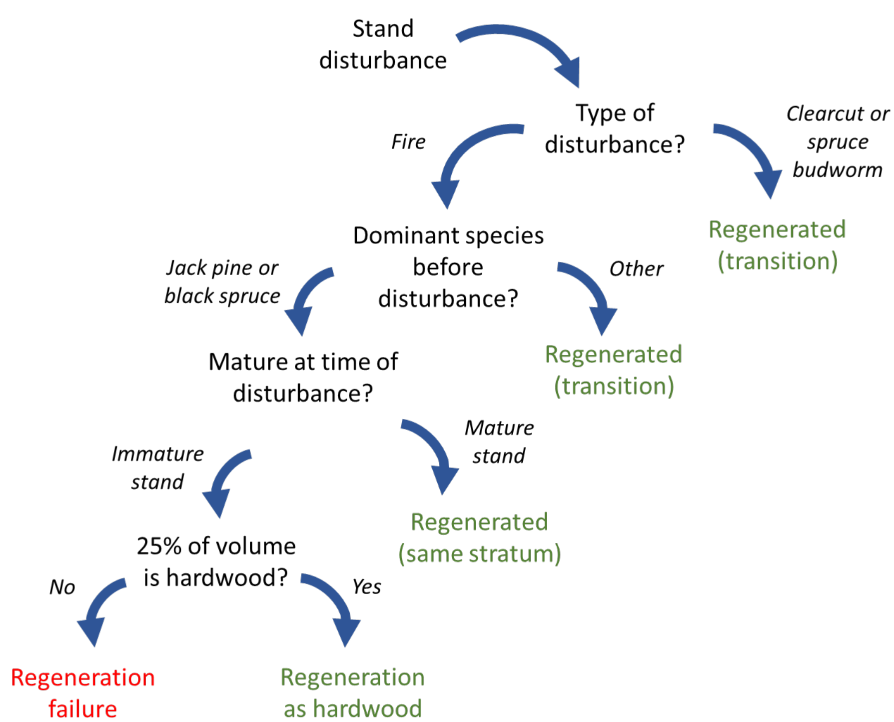


Figure 8. Illustration of the decision rules that lead to either regeneration of disturbed cells (in green), or to regeneration failure (in red).

3.2.4.5. Forest harvesting and pre-commercial thinning

Three modules, representing three distinct silvicultural treatments, remove timber volume from the forest: clear-cut harvesting, salvage logging, and pre-commercial thinning. Only salvage and clear-cut logging generate merchantable wood volume that contributes to reaching the time period's harvest target (section 3.2.4.8); harvested volumes are tabulated separately for softwood and hardwood volumes. When one of these three treatments is applied to a cell, the cell is identified as anthropogenically disturbed for the purpose of assessing disturbance rates (section 3.2.4.9). Short descriptions of these treatments are shown in Table 5.

Salvage logging recovers salvageable wood volume from recently burnt stands. The effect of fire on merchantable volume is presented in the section on fires (section 3.2.4.1). When fires are included in a simulation, the model seeks to meet its harvest target by first harvesting salvageable volume. Salvage logging can only take place within managed forest.

To be eligible for clear-cut harvesting, a cell must:

- Be located within the managed forest
- Have attained minimum harvest age, and
- When old forest constraints are in effect, be located within a territorial analysis unit where the proportion of old forest is greater than the minimum proportion of old forest for that unit.

After harvesting available salvageable volume, the model prioritizes harvesting in intensive management zones (section 3.2.4.1). Following intensive management zones, the module prioritizes the harvesting of stands by age, starting with the oldest stands.

When a stand has been disturbed, the model determines whether the stand will be eligible, once the minimum age has been reached (15 years), for pre-commercial thinning. Each simulation year, the model then proceeds to pre-commercial thinning of eligible areas until the maximum area defined in the development strategy (section 3.1.2) is reached.

3.2.4.6. Tree planting

Two situations lead the model to establish a stand through tree planting:

- Following the clear-cut harvesting of a management strata for which planting is a possible transition, as specified in the management strategy and
- Regeneration failure following the passage of fire.

The model establishes plantations until the annual area-based planting limit specified in the management strategy (section 3.1.2) is reached. In the context of this project, tree planting in intensive management zones is not constrained by the annual planting limit.

3.2.4.7. Creation of intensive management zones

Intensive management zones were established through an analysis of available data. The spatial organization compartments[15] with the greatest proportion of high productivity forest were identified, and the top 25% (on an area basis) were retained as intensive management zones for the project. Only sites with strata eligible for planting were retained. The area identified as intensive management zones is shown in Figure 9.

[15] TN: « Compartiments d'organisation spatiale », or COS, in French.

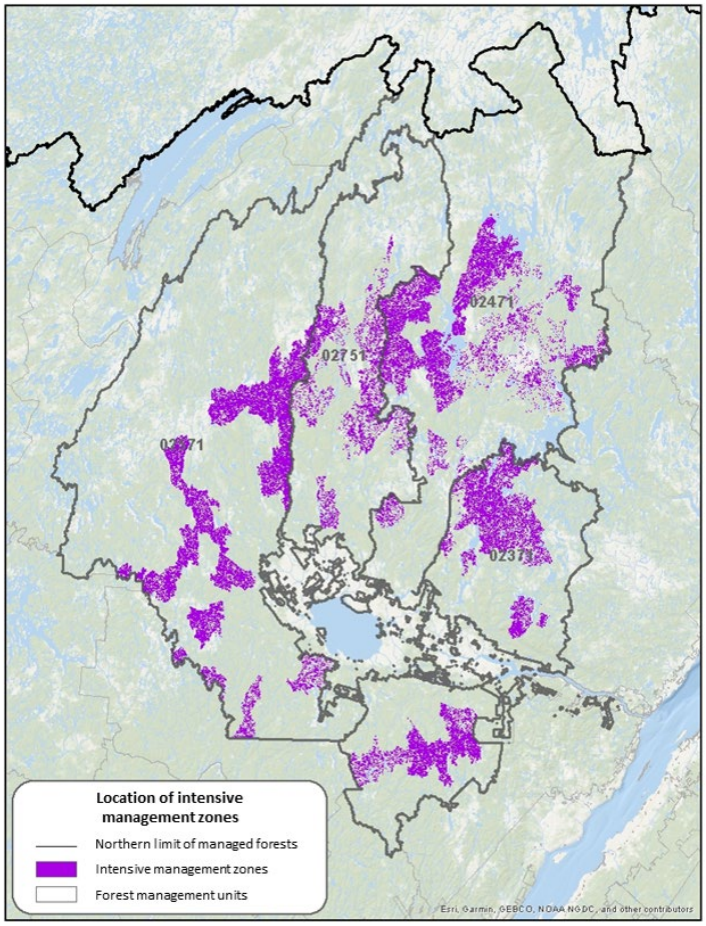


Figure 9. Location of intensive management zones (in purple); together, these zones represent approximately 25% of the area of managed forest.

In these zones, planting area limits and old forest constraints do not apply as these areas are dedicated to timber production. Therefore, when a natural or anthropogenic stand-replacing disturbance occurs in cell located within an intensive management zone, the cell is automatically planted. Planting effort is therefore focused in these more productive areas.

3.2.4.8. Estimation of annual harvest rates

Two methods were applied to establish harvest levels within the BFEC-CC model: (i) the quantification of maximum sustained yields through binary search and (ii) the imposition of pre-determined harvest levels. These two processes are described in the following sections.

Maximum sustained yield harvest levels

The maximum sustainable harvest level is established iteratively, through trial and error, using a binary search algorithm. To achieve this, the model begins by testing an arbitrary harvest level, for example the harvest level obtained in the last allowable cut calculation. If there are no harvesting shortfalls during the simulation (if the tested harvest level can be reached in all periods), the model then attempts a higher harvest level. If, as in Figure 10, the first trial generates shortfalls during simulation, a lower harvest level is tested for the next iteration. The model thus continues to test harvest levels until the difference between (A) the highest harvest level tested that did not cause shortfalls and (B) the lowest harvest level tested leading to shortfalls are separated by at most 2.5% of the initial arbitrary harvest level. The maximum sustained yield harvest level is then level A, the highest harvest level not causing a shortfall during the simulation.

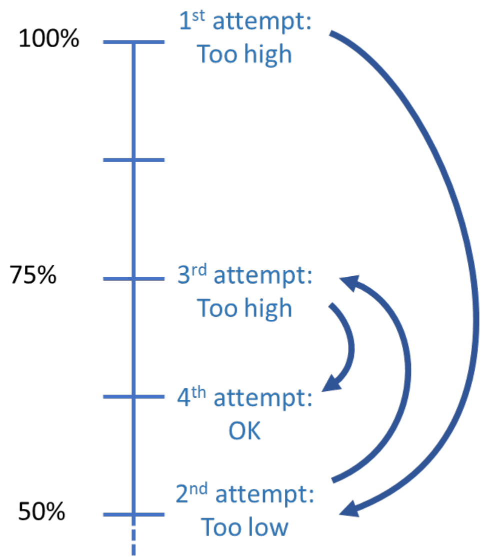


Figure 10. Illustration of the binary search applied to the process of maximizing sustained yield harvest rates.

Imposition of variable harvest rates

The other method for setting harvest levels within the model involves the imposition of harvest levels according to a schedule of harvest rates established in advance. The model therefore tries to reach the harvest target in every simulation period, and records a shortfall if this target is not reached. This method allows the testing fixed harvest levels or the effect of a harvest levels that decreases or increases over time. When harvest levels decrease over time, the phenomenon is akin to the "fall-down effect" as it has been called in British Columbia[16].

3.2.4.9. Evaluation of caribou disturbance rates and habitat

Caribou habitat disturbance rates are assessed by the model at each time step. The model places 500-meter buffer zones (Environment Canada 2011) on anthropogenic disturbances (harvesting, salvage cutting, pre-commercial thinning, and planting), and measures the area occupied by these buffers and by natural disturbances (fire and severe mortality due to the budworm) by territorial analysis unit. Natural and anthropogenic disturbances are considered to influence woodland caribou habitat for a period of 50 years. The area disturbed is then expressed as a percentage of the total area of the territorial analysis unit.

3.2.4.10. BFEC-CC model outputs

The BFEC-CC model generates a significant amount of output data. For each simulation, the model generates 34 separate files, each containing information on, for example, the state of the forest, silvicultural treatments applied, harvest level (conifers, deciduous and salvage after fire), and the quantity of caribou habitat at each time period. A complete list of output files is presented in an appendix.

Spatially explicit outputs are also produced by the model, although they were not used for the analyses presented in this report. Spatial outputs were mainly used to validate the proper functioning of the model during development.

3.3. Iterative process of learning and scenario design

Because the development of adaptation measures for forest management required sustained learning, a dynamic process for decision-support (section 2.6) was implemented. Results were presented to the Chief Forester and regional planners and their recommendations on potential solutions and scenarios to test were taken into account.

[16] https://www.for.gov.bc.ca/hfd/library/documents/glossary/1990s/F.htm.

3.3.1. Development of adaptation measures

Once the model was made functional, preliminary scenarios were tested to simulate the effect of climate change on the forest without adaptation measures. Sensitivity analyses, aimed at testing the interactions among the different processes modelled (section 2.4), were also tested. Most of these scenarios are presented in Table 12.

Table 12. Processes modelled in the context of the preliminary scenarios, tested with the BFEC-CC model.

Scenario name	Simulated components					Old forest constraint
	Productivity	Wildfire	Spruce budworm	Regeneration failure	Forest management	
Prod	☑	☒	☒	☒	☑	☑
ProdFire	☑	☑	☒	☒	☑	☑
NoManagement	☑	☑	☑	☑	☒	-
StatusQuo	☑	☑	☑	☑	☑	☑
WithoutOF	☑	☑	☑	☑	☑	☒

Based on the results of these preliminary scenarios, participants could draw a number of conclusions about the behaviour of forests under climate change and management actions. These conclusions, referred to as "learnings"[17], served as starting points for the development of (i) a better understanding of the behaviour of the modelled forest under climate change and (ii) a range of management actions called "adaptation measures", which seek to overcome, or draw some benefit from, the effects of climate change on forests.

Through a succession of collective learnings, the development of adaptation measures becomes an iterative process seeking satisfactory solutions to challenges encountered under climate change. Adaptation measures are not predetermined, but result from a review of literature and the sharing of expertise by those involved in the process. As learning progresses, adaptation measures are combined in order to investigate potential synergies that may lead to better outcomes. Several measures were evaluated during the project and the most important are presented in Table 13.

Table 13. The adaptation measures tested as part of a number of management scenarios. The *Status quo* scenario is included to facilitate the comparison of this scenario with scenarios testing adapting measures.

Scenario names	Intensive management zones	Extensive management		
		Old forest constraints	% of planted area as deciduous	Area planted, relative to *Status quo*
Status quo	☒	☑	0%	1X
D100	☒	☑	100%	No area limit
Intensive	☑	☑	0%	1X
Intensive_D50	☑	☑	50%	1X
Intensive _D50_Plant2	☑	☑	50%	2X

[17] TN: In the original text, the expression « apprentissage » was employed as a countable noun to denote an instance when something specific is learned by project participants. Therefore the word « learning » as a countable noun, commonly used in English though not broadly accepted, is used here.

Modification of the BFEC-CC model was occasionally required to allow it to address new questions or simulate new adaptation measures; descriptions of these modifications are included in the methods section above (section 3.2.2). In total, nearly a hundred different forest management scenarios were tested in the context of this project.

3.3.2. Evolution of the decision-support process

3.3.2.1. Identification of a suite of indicators to support decision-making

Identifying the management objectives that are significant to decision-makers is an important step in decision support. For the project, key management objectives were translated into measurable indicators. It was considered important to cover the principal dimensions of the problem space. The dimensions of "Sustainability", "Feasibility" and "Intergenerational equity" were thought to cover the full range of issues. Table 14 lists the indicators selected and assessed to inform decision-making. These indicators were used to compare the tested adaptation scenarios.

The indicators retain their own units of measurement, as it is not desirable at this stage to attempt to aggregate them into a single measurement scale. Also, each indicator was labelled as needing to be either maximized or minimized (Table 14).

Table 14. Indicators retained for the decision-making process.

Indicators	Measurement units	Objective
Proportion area as old forest	% of forested area	Maximize
Proportion area as regeneration failure	% of forested area	Minimize
Caribou habitat disturbance rate	% of land area	Minimize
Mean area planted annually	ha/year	Minimize
Proportion of harvested volume from salvage	% of harvested volume	Minimize
Harvest rate	m^3/year	Maximize

3.3.2.2. Evaluation of scenario outcomes

An assessment matrix for scenarios and adaptation measures, expressed in terms of the indicators selected, was constructed from modelling results. Since the model evaluates indicator values for each year of the 150-year time horizon, results were aggregated as a function of time. Averages for the short, medium, long, and very long terms (Table 15) were calculated. This approach aims to simplify communication by simplifying the temporal dimension of results, and the size of the evaluation matrix to be analyzed by decision-makers.

Table 15. Time periods used to synthesize results over time.

Time period	Simulation years
Short term	2020 to 2050
Medium term	2051 to 2075
Long term	2076 to 2120
Very long term	2121 to 2170

Indicators were evaluated for each adaptation scenario, according the range of climate scenarios retained for use in this project (3.2.1). The evaluation matrix created is shown in Table 16.

Table 16. Outline of an evaluation matrix for a given indicator.

Adaptation scenario	Time period	Indicator values		
		Historical climate	RCP 4.5	RCP 8.5
A	Short term	A_1	A_2	A_3
	Medium term	A_4	A_5	A_6
	Long term	A_7	A_8	A_9
	Very long term	A_{10}	A_{11}	A_{12}
B	Short term	B_1	B_2	B_3
	Medium term	B_4	B_5	B_6
	Long term	B_7	B_8	B_9
	Very long term	B_{10}	B_{11}	B_{12}

3.3.2.3. Modelling preferences

The comparative performance of two adaptation scenarios can be interpreted in many different ways, in part because elements such as satisfaction, threshold of perception, uncertainty, and imprecision come into play. It is essential to specify the discriminating power of indicators. According to Roy (1985), discriminating power represents "the more or less marked faculty to discriminate situations of strict preference, indifference, and weak preference between two actions on the basis of the difference in their evaluations".

Within the framework of a project such as this one, a decision-maker can be more or less tolerant of variations in an indicator’s values over time, and accept compromises more or less easily on certain indicators. For example, the decision-maker may be indifferent to variations of ± 5%, prefer one adaptation measure to another because an indicator value is 10% higher, or reject a particular adaptation measure because an indicator has exceeded its tolerance threshold. Preference, discomfort, and rejection intervals are thus introduced to select the most promising adaptation measure and to help stimulate the development of new measures that may perform better.

Also, all indicators may not have the same importance for a decision-maker, and the relative importance of each indicator may vary over time.

At this stage of preference modeling, weighting methods are commonly applied. Thus, the decision-maker is asked to specify the discriminating power that should be assigned to each indicator. For example, the decision-maker can rank indicators from most to least important, and then attribute 100 weighting points among the indicators. The scores reflect the importance to be placed on indicators when making decisions. This exercise provides the basis through which relationships among indicators can be understood. Table 17 shows information related to the discriminating power of indicators that is required from the decision-maker.

Table 17. Decision-maker preferences

Indicators	Weights	Threshold values		
		Preference	Discomfort	Rejection
A	P_1	A_1	A_2	A_3
B	P_2	B_1	B_2	B_3
C	P_3	C_1	C_2	C_3

This step of decision support involves a good deal of subjectivity, which is expressed in terms of the decision-maker’s values and objectives. For the purposes of the project, threshold values were set by the project team. The weights applied to the indicators were all equal to 1, both for comparisons among indicators and for comparisons among time periods.

3.3.2.4. Analysis of trade-offs among adaptation scenarios

Although an adaptation scenario can improve on an indicator's performance relative to other scenarios, the improvement in one indicator's performance may come at the cost of another indicator's performance. To analyze the trade-offs among each adaptation scenario tested, scenario results were represented in the form of radar graphs. To prepare the data, each indicator's data for each time period was standardized so that the maximum value was 1 and the minimum value was zero; all other values were scaled accordingly. Thus, the value 1 represents the best performing value for the indicator and time period, while the value 0 represents the worst performing. As the weights associated with each period were equal, the sum over all periods of the standardized values per period was used for the graphs. The radar graphs thus represent the performance of indicators for the scenarios tested over the entire simulation time horizon.

3.3.2.5. Ranking of adaptation scenarios according to objectives

The final step in this decision support process is to aggregate available information in order to facilitate an identification of the most satisfactory solution or solutions from the decision-maker's perspective. Many aggregation procedures have been developed as a function of the issues encountered. However, the choice of a multicriteria aggregation procedure should be based on the nature of the decision problem at hand (Bana e Costa, 1996). Roy (1985) defined four types of decision problems, and how these influence the choice of multicriteria aggregation procedure:

- The **choice problem** guides the selection of actions (or scenarios, in the case of this project) in order to highlight a subset which contains the best solution. It consists of choosing a single "best" solution.
- The **sorting problem** involves the classification of actions (or scenarios) into different categories, which were defined *a priori*, in order to separate the best solutions from the worst.
- The **ranking problem** consists of sorting potential actions (or scenarios) from the most satisfactory to the least satisfactory, by grouping solutions into classes. Classes are not defined *a priori* as is the case with sorting problems. All actions (or scenarios) are then sorted according to preference classes; ties are therefore possible (Martel, 1999).
- The **description problem** is a procedure that helps the decision-maker to gain a better understanding of the different potential actions (or scenarios). The method involves describing potential actions (or scenarios) and their consequences so as to help the decision-maker understand and evaluate them, in a context where actions are revisable and sometimes temporary.

In the context of this project, the decision-maker is confronted with a ranking problem, where adaptation scenarios can be ranked from best to worst. The description problem is also present, since the development of solutions is iterative and dynamic, and learning eventually leads to more refined and better solutions, which in turns leads to further learning.

To address the ranking problem, a relatively simple method was used to rank adaptation scenarios from best to worst. To do this, a score between zero and one was first assigned (3.3.2.4) to each of the cells of the evaluation matrix (Table 16), as described above. Then, for a given indicator at time period, scenario evaluations are assigned a score, from the best evaluation to the worst, by accepting ties if the values are sufficiently close. The score of "1" was awarded to the best performance, "2" to the next best, and so on. This process is performed for each of the indicators for the climate scenarios separately. The individual scores are then summed by modality. The higher the score, the more the modality deviates from the expected performance of the modality. An ideal score would be equal to the number of indicators assessed, as all summed values would be equal to "1". The scoring exercise takes into account the measurement scale, whether indicators should be maximized or minimized, according to the nature of the indicator.

The results obtained can be interpreted by time period or globally by scenario. One of the advantages of this method is that it allows, for each time period, the identification of the best performing scenario. These "segments" (i.e., scores by time period) can be used as building blocks and help to develop more effective adaptation measures as the decision-support process evolves.

For the purposes of this project, existing multicriteria aggregation methods could not be applied. These aggregation methods should be studied further and adapted to better suit the complexity of the decision support process.

4. Results and discussion

4.1. Learnings

The learnings established during the project are presented here in the order in which they were acquired. It is important to note that these learnings were identified based on the results of the BFEC-CC model and the assumptions that were therein incorporated. A different set of learnings would have been identified if other models or other assumptions had been used.

4.1.1. Preliminary learnings

Simulation results for the preliminary scenarios (section 3.3.1) provided a basic understanding of the behavior of the BFEC-CC model and the possible impacts of climate change on the region's forests without adaptation measures. The learnings drawn from these results are presented in the following sub-sections.

4.1.1.1. There are important differences among climate scenarios, but not among climate models

Examination of modeling results from BFEC-CC indicates that while there are often significant differences among results for different climate scenarios (historical, RCP 4.5, RCP 8.5), the three climate models (ESM) often lead to comparable results (Figure 11). Therefore, only results of the Canadian model (CanESM2) are presented in the following sub-sections.

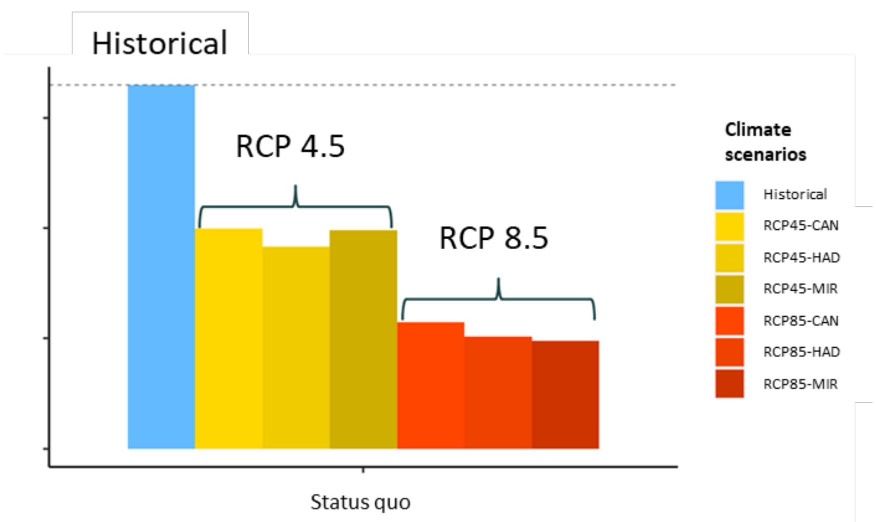


Figure 11. Illustration of the divergence of results from different climate scenarios (RCP) and convergence among results for different earth system models (ESM) but for the same climate scenario.

4.1.1.2. Even without harvesting, there will be significantly less area as closed forest and old forest under climate change

When simulations are run with fire and the potential for regeneration failure but without adaptation measures, simulation results indicate that, after 150 years of simulation under climate change, there is more area as unregenerated forest (open forest or heathland) and, at the same time, less area as old-growth forest (Figure 12). Regeneration failures are caused by the passage of fire in stands that have not reached reproductive maturity (3.2.4.4).

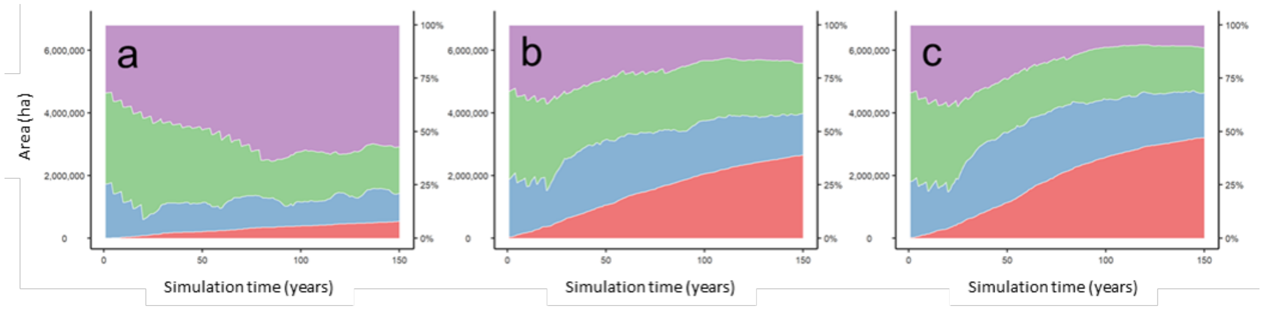


Figure 12. Diagrams illustrating the abundance of age classes without forest management under (a) the historical climate, (b) RCP 4.5, and (c) RCP 8.5. Area as regeneration failure is shown in red, regenerating area is shown in blue, premature and mature forest is in green, and old forest is shown in violet.

4.1.1.3. Under climate change, fire return intervals will be shorter

The results obtained in this study are consistent with the results of the research work that was used to drive the simulation of fire (Boulanger et al. 2014 and 2017). Under climate change, fire cycles will be much shorter than in the past. In fact, the fire cycle under status quo management, which was 300 years under a historical climate, decreases to less than 100 years under climate change (Figure 13) on average over the simulation period. It should be noted that the more severe climatic conditions (from 2071 to 2100) are maintained in the model over a period more than three times longer (from 2071 to 2170) than the climatic conditions 2011-2040 or 2041 to 2070.

This learning led to the development of the hardwood enrichment adaptation measure, which seeks to manipulate forest landscape composition so as to influence the fire regime (section 4.1.2.1).

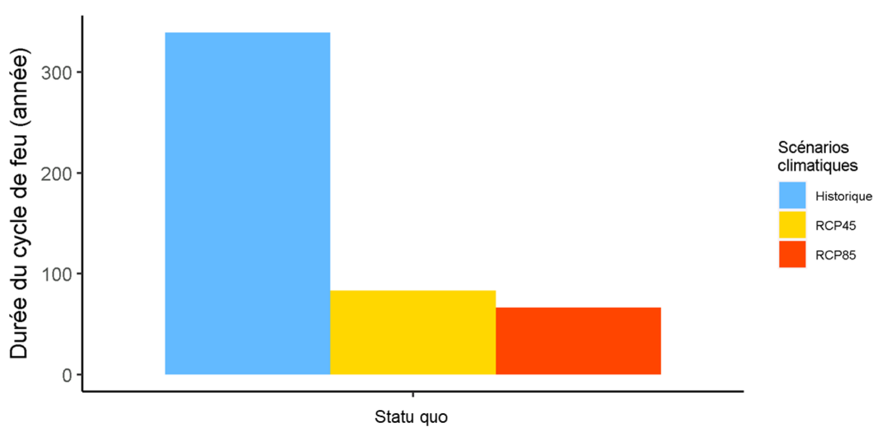


Figure 13. Mean fire return interval under Status quo management for the three climate scenarios tested.

4.1.1.4. The gains in productivity for conifers due to climate change will be small and transitory

When corrections for climate change effects are applied to merchantable volume (3.2.4.3), the results show that, on average, the productivity of softwood species increases slightly over the next 50 years and then decreases below historical values for the remainder of the simulation period. Also, under RCP 4.5 (Figure 14a) and RCP 8.5

(Figure 14b), conifer productivity is higher than historical values (i.e., the climate change volume multiplier is greater than 1) for a period of approximately 50 years (from 2020 to 2070). From that point onward, conifer productivity decreases below historical levels, most notably under the RCP 8.5 climate scenario.

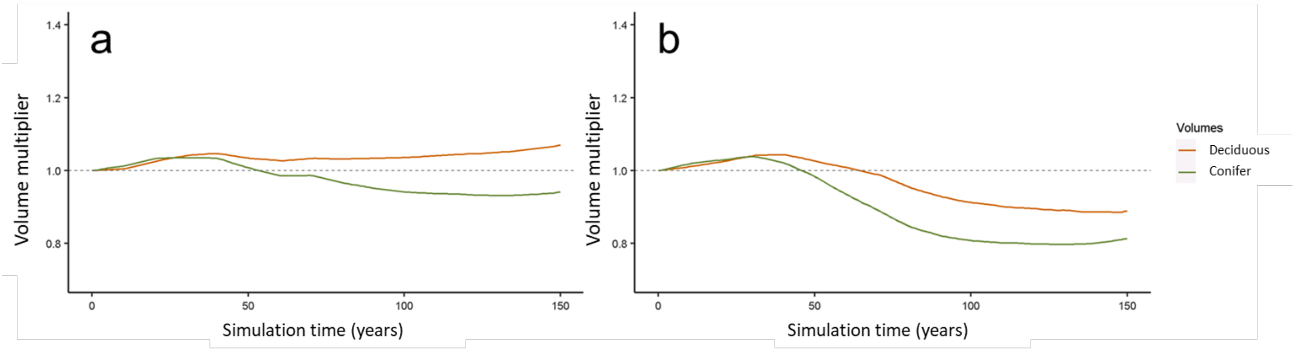


Figure 14. Mean values of merchantable volume multipliers (weighted by area) over 150 years of simulation for the status quo scenario under (a) RCP 4.5 et (b) RCP 8.5 for conifer (in green) and deciduous (in orange) merchantable volumes. The dotted horizontal line indicates a multiplier, equal to 1, under a historical climate.

The productivity of hardwoods remains, on average, higher than historical productivity under the RCP 4.5 climate scenario (Figure 14a). Under RCP 8.5, the productivity of hardwood species remains higher than historical values for a period of approximately 70 years, but falls below historical values thereafter (Figure 14b).

4.1.1.5. Over a 150 year period, gains in productivity will not be sufficient to compensate for the effect of fires

Increased forest productivity early during simulation (Figure 14) results in a slight increase in harvest levels at maximum sustained yield when fires are not included in the simulation (Figure 15, left). However, when fires are included in simulations (Figure 15, right), the effect of increased productivity is not sufficient to compensate for the negative effect of fires on the availability of harvestable wood volumes.

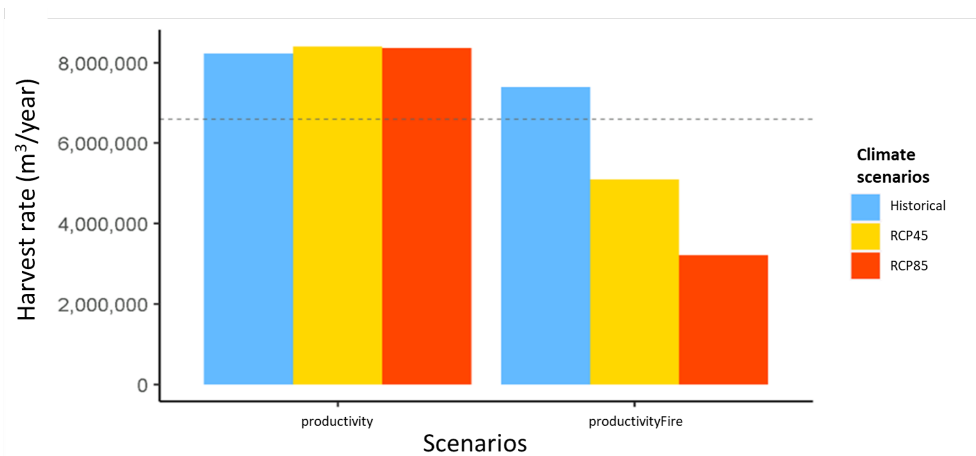


Figure 15. Harvest rates under the status quo management scenario, integrating the effect of climate on productivity only (left) and the same scenario but with the inclusion of fires (right). No other disturbance was included in these simulations. For each simulation, the harvest rate reflects the maximum sustained yield harvest rate given the assumptions provided.

4.1.1.6. Under climate change, the effect of spruce budworm will diminish over time

The area affected by severe mortality as a result of spruce budworm defoliation decreases significantly under climate change. Under the status quo management scenario, this area is on average greater than 6,000 hectares per year (over all the simulation years) under a historical climate, less than 2,000 hectares per year under RCP 4.5, and less than 1,000 hectares under RCP 8.5. The annual patterns of severe mortality due to the budworm under the three climate scenarios are presented in Figure 16. Higher mean annual temperatures under climate change appear to make the region's forest less suitable for the insect. A greater abundance of young forest is also partly responsible for this effect (Table 9). Sensitivity analysis would be needed to further clarify the relative importance of causal factors.

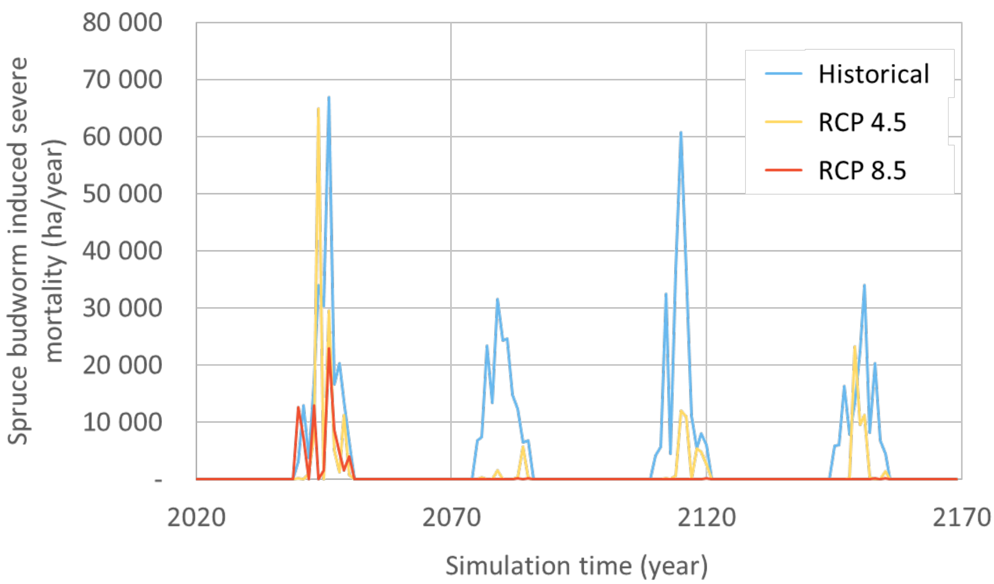


Figure 16. Area affected annually by severe mortality due to spruce budworm defoliation under the three climate scenarios.

4.1.1.7. Maintaining the current strategy under climate change will lead to much lower maximum sustained yield harvest levels than under a historical climate

By applying the status quo management strategy and with all disturbances activated within the model (fire, budworm, effect on productivity, and regeneration failure), harvest levels decrease significantly as compared to historical levels. Climate change leads to a drop in harvested volume of 39% under RCP 4.5 and 65% under the RCP 8.5 scenario (Figure 17).

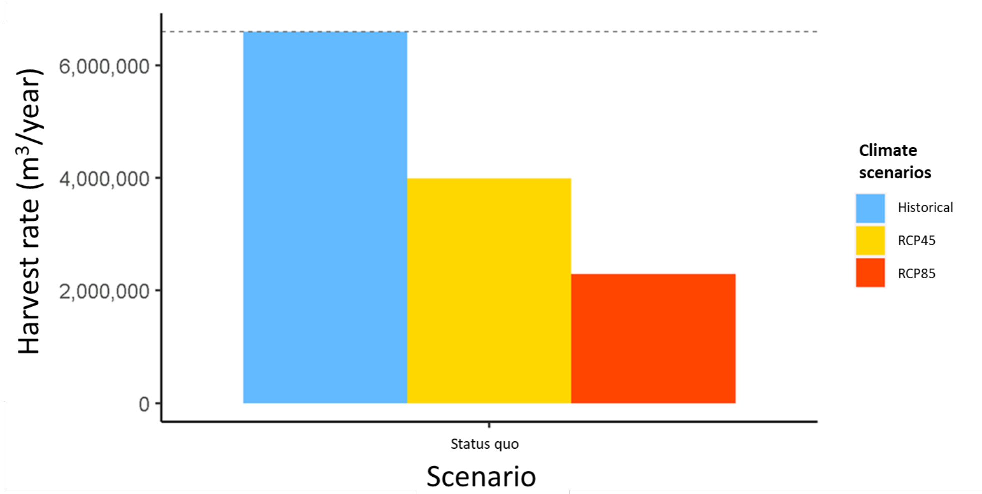


Figure 17. Maximum sustained yield harvest rates obtained for the status quo management scenario under the historical, RCP 4.5, and RCP 8.5 climate scenarios.

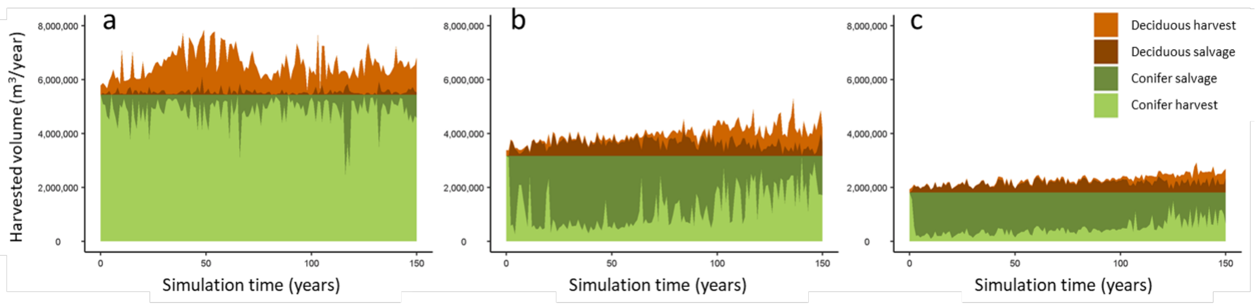


Figure 18. Annual conifer (in green) and deciduous (in orange) volume harvested over the 150-year simulation period with status quo forest management under (a) historical, (b) RCP 4.5, and (c) RCP 8.5 climates. Volumes salvaged after fire are represented in a darker shade (dark green for conifer and dark orange for deciduous volumes).

It should be emphasized that under the RCP 4.5 and RCP 8.5, a significant proportion of harvested volume is salvaged from burnt stands (Figure 18b and Figure 18c). Salvageable volume, which is harvested ahead of live tree volumes, decreases towards the end of the simulation despite an increase in area burned (4.1.1.3) because, as the forest becomes gradually younger, less standing volume is eligible for post-fire recovery (section 3.2.4.5).

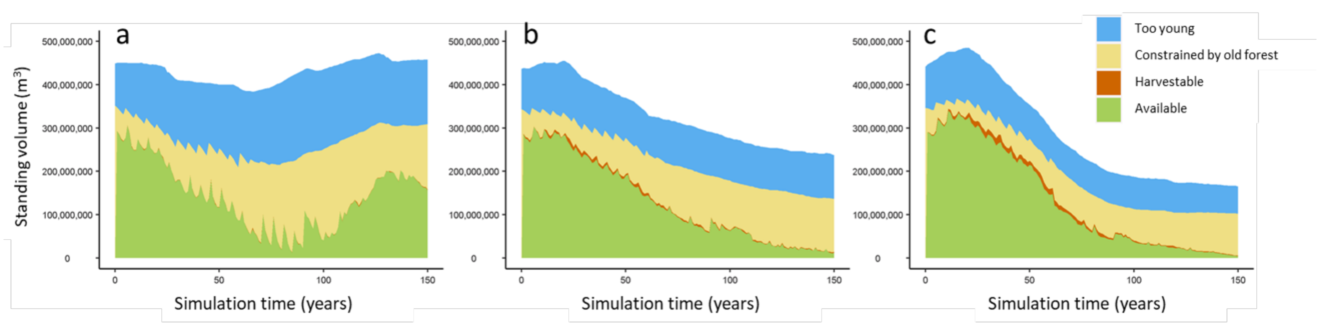


Figure 19. Standing volume in the study area under the status quo management scenario under the (a) historical, (b) RCP 4.5, and (c) RCP 8.5 scenarios. Volumes that are available for harvest are shown in green (live trees) and orange (salvage).

Under a historical climate, the timber supply pinch point for the region is at approximately 75 years (Figure 19a). Under climate change, pinch points occur at the very end of the simulation period (Figure 19b and Figure 19c for RCP 4.5 and RCP 8.5, respectively).

4.1.1.8. The accumulation of area where regeneration has failed makes old forest targets more difficult to attain

For the status quo management scenario under climate change, there is a significant accumulation of area where regeneration has failed (Figure 20b and Figure 20c). This reduction in productive forest area makes it more difficult for the model to meet old forest targets. This issue contributes significantly to the drop in harvest levels under climate change (Figure 17). Indeed, when the old forest constraint is removed, significant volumes that were previously unavailable (Figure 19) becomes available for harvest (Figure 21).

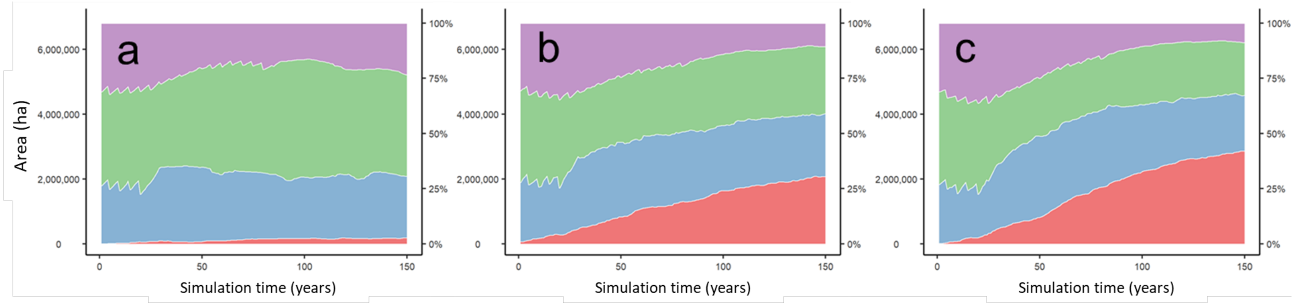


Figure 20. Diagrams illustrating the abundance of age classes for status quo management under (a) the historical climate, (b) RCP 4.5, and (c) RCP 8.5. Area as regeneration failure is shown in red, regenerating area is shown in blue, premature and mature forest is in green and old forest is shown in violet.

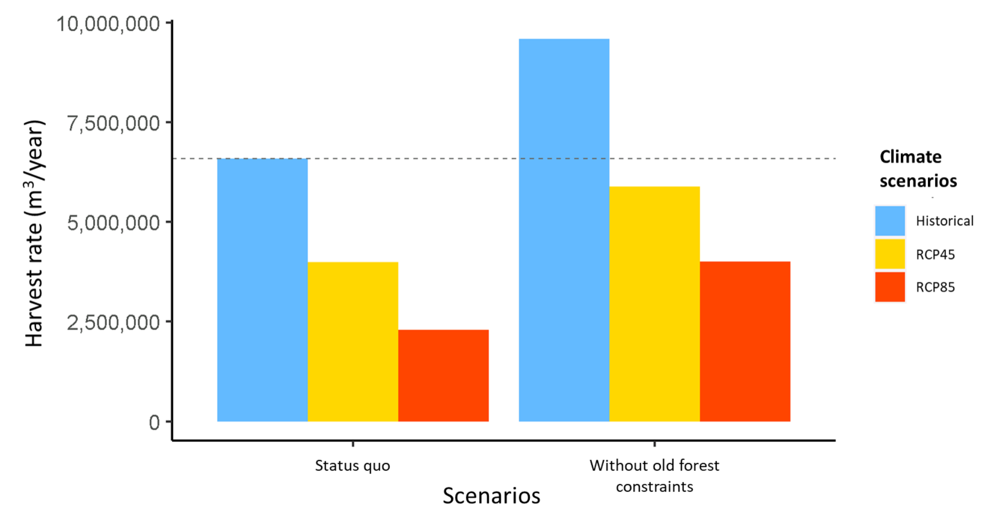


Figure 21. Sensitivity analysis showing the effect of the old forest constraint on harvest levels.

4.1.1.9. Without adaptation, maximum sustained yield harvest levels established under a historical climate are not sustainable under climate change

Given the assumptions applied to the modelling, results (Figure 22) show that the current (status quo) management strategy is not sustainable under climate change.

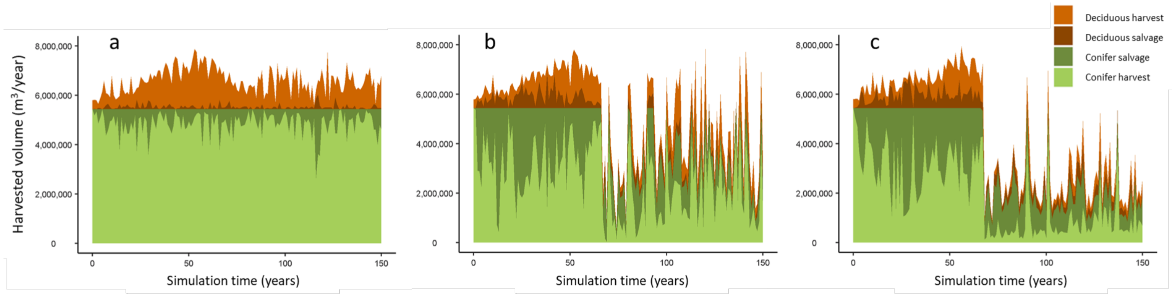


Figure 22. Annually harvested volumes under the status quo management scenario, under the (a) historical, (b) RCP 4.5, and (c) RCP 8.5 scenarios. The harvest rate under the historical climate is the maximum sustained yield harvest level. The harvest levels under RCP 4.5 and RCP 8.5 is the maximum sustained yield harvest level obtained under a historical climate, while allowing harvesting shortfalls to occur when sufficient wood volumes are not available in a given time period.

4.1.2. Learning obtained through the simulation of adaptation measures

Having established certain preliminary learnings (section 4.1.1), the search for solutions (i.e., the development of adaptation measures) could be undertaken. The learnings drawn from adaptation scenario simulation results are presented in the following sub-sections, in an order roughly corresponding to the chronology of their development.

4.1.2.1. Significant enrichment in deciduous species leads to harvested volumes that are dominated by deciduous volumes

Under the current management strategy for the study region, plantation always aims to establish conifer stands. In the context of this project and partly to counter the effect of wildfires, an adaptation measure was tested whereby a deciduous stand is established each time tree planting is invoked by the model (section 3.2.4.6) and in all cases where regeneration fails (section 3.2.4.4). Under this adaptation scenario, the landscape gradually converts to a predominantly deciduous forest. This adaptation measure requires intervention, in the form of plantation, over a large area annually and results in harvested volumes that are principally deciduous (Figure 23). Discussions with project partners emphasized the importance of conifer volumes for the region's forest industry. This learning led to the development of adaptation measures where only partial enrichment in hardwoods is applied (section 4.1.2.3).

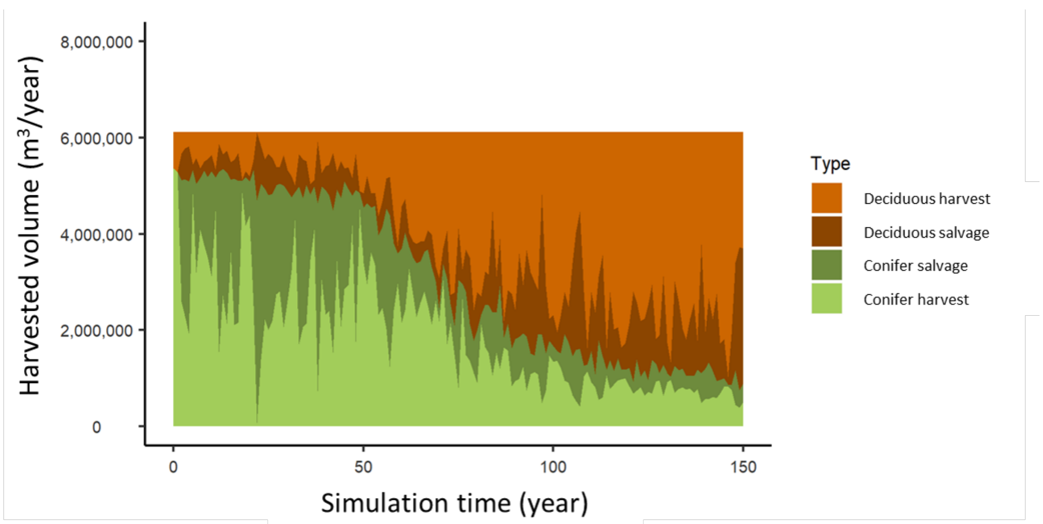


Figure 23. Harvested volumes under the deciduous enrichment scenario over the 150-year simulation period, under the RCP 4.5 climate scenario.

The results of the deciduous enrichment measure show that it is possible to reduce the flammability of forests (Figure 24), tracked using the Bernier et al. (2016) correction factor, while maintaining productive forest on the landscape. The flammability of the forest also decreased with time under the status quo scenarios, but this effect was mainly due to a drop in mean stand age and an increase in the area as regeneration failure.

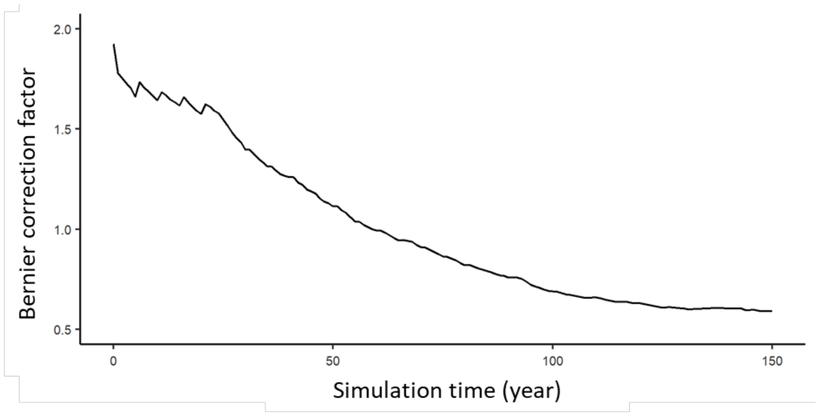


Figure 24. Evolution of the Bernier et al. (2016) correction factor while simulating the deciduous enrichment scenario and the RCP 4.5 climate scenario. A higher correction factor leads to a greater annual area burned. A correction factor of 1 corresponds to a burn rate from which the effect of forest composition has been removed (section 3.2.4.1).

This measure contravenes the "natural dynamics" element of the Sustainable Forest Development Act (section 1.1 of this report) while at the same time respecting the element of "maintenance and improvement of the productive capacity of forests" in the Act.

4.1.2.2. The creation of intensive forest management zones significantly increases maximum sustained yield harvest rates under climate change

Through the application of intensive forest management zones to 25% of the managed forest, harvest levels increased by 38% and 39% under the RCP 4.5 and RCP 8.5 climate scenarios, respectively. This effect is partly due to the fact that the old forest constraint does not apply to intensive management zones. Intensive management zones are replanted immediately following disturbance, whether natural or anthropogenic, which leads to significant areas of plantation every year (section 4.2.2).

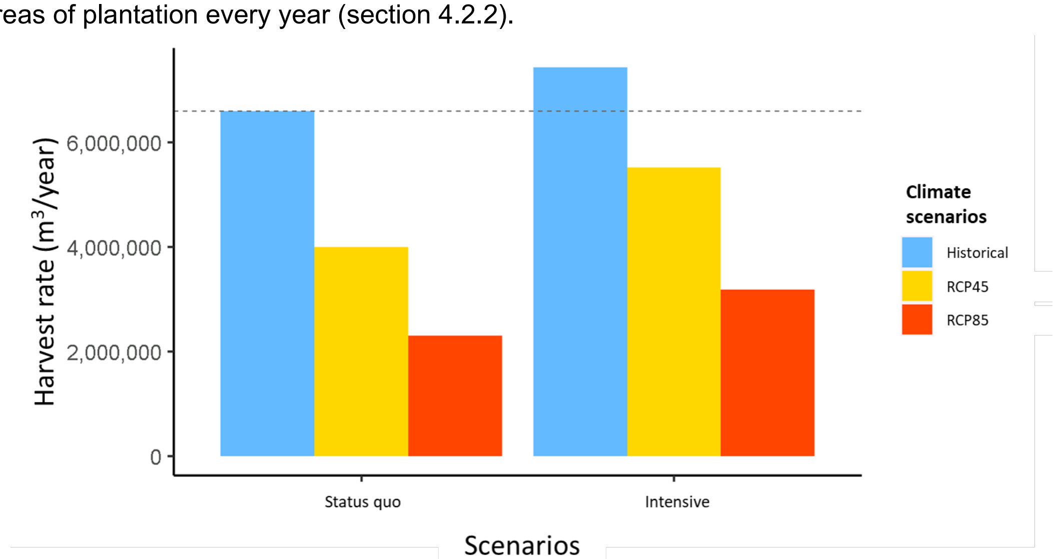


Figure 25. Comparison of harvest levels under the status quo (left) and intensive management zones adaptation (right).

4.1.2.3. Enrichment with deciduous species outside intensive management zones somewhat increases maximum sustained yield harvest levels

In a subsequently tested adaptation scenario, two adaptation measures were included along with intensive management zones ("Intensive"): (i) alternately planting deciduous and conifer species in the extensive management zones after disturbance, over an area and for the strata specified by status quo management strategy ("Intensive_F50") and (ii) alternating deciduous and conifer plantation, but doubling the planted area in relation to status quo management ("Intensif_F50_Plant2").

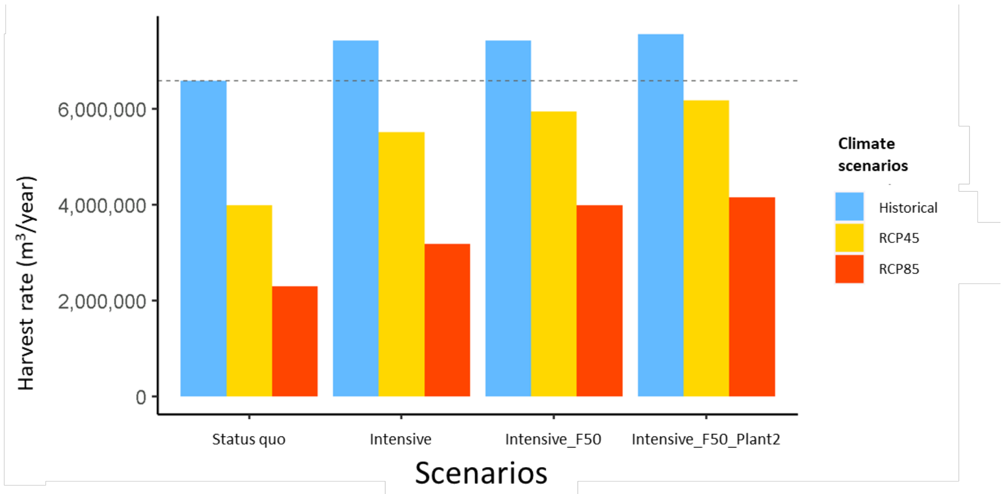


Figure 26. Comparison of harvest levels under the status quo, intensive management, intensive management with partial deciduous enrichment in the extensive management zone, and the latter scenario with a doubling of annually planted area.

Under climate change, the adaptation measures of alternating deciduous and conifer plantation (Intensif_F50) and doubling of the area planted (Intensif_F50_Plant2) somewhat increase harvest levels (Figure 26). These increases are mainly the result of greater harvested deciduous volume; conifer harvested volumes do not increase appreciably under these scenarios (Figure 27).

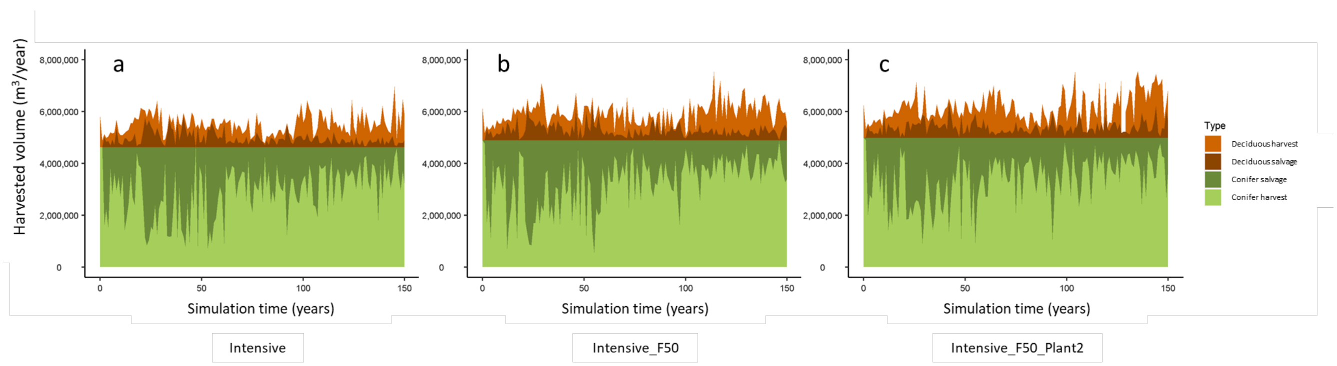


Figure 27. Annually harvested volumes under the (a) Intensive, (b) Intensive_F50, and (c) Intensive_F50_Plant2 adaptation scenarios.

4.1.2.4. Enrichment with deciduous species outside intensive management zones significantly decreases the area as regeneration failure after 150 years of simulation

Although harvest levels increase very little under the deciduous enrichment adaptation measures, these measures significantly reduce the accumulation of area as regeneration failure after 150 years of simulation (Figure 28). This results to a great extent from the assumptions applied in the BFEC-CC model. Indeed, in the model deciduous-dominated stands are more resilient under more intense fire regimes, because these stands are not susceptible to regeneration failure (section 3.2.4.4). Like the deciduous enrichment adaptation measure (section 4.1.2.1), these modalities contravene the "natural dynamics of forests" element while, at the same time, respecting the element of "maintaining the productive capacity of forests" of the Sustainable Forest Development Act (section 1.1).

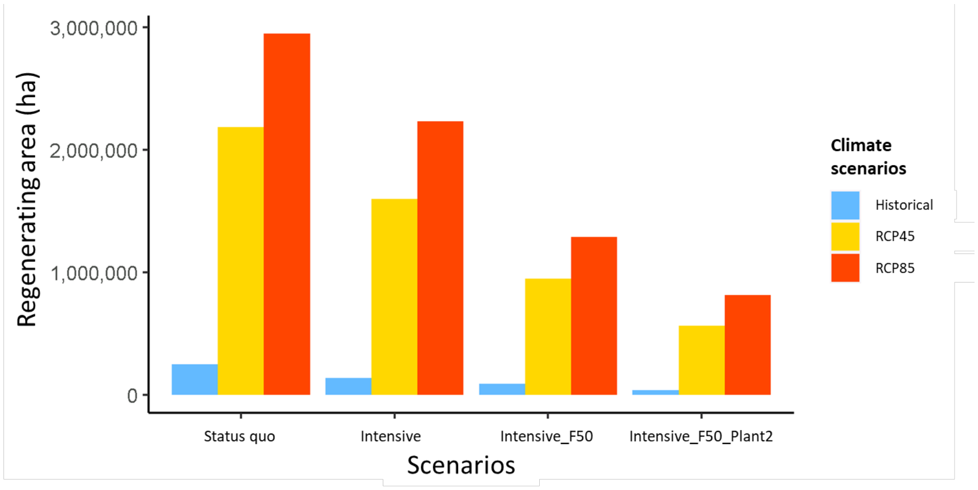


Figure 28. Regenerating area after 150 years of simulation under the status quo management scenario and three adaptation scenarios.

4.1.2.5. Adaptation measures can alleviate harvesting shortfalls under climate change

Under climate change, the application of the Intensive_F50_Plant2 adaptation scenario considerably reduces the number of years experiencing shortfalls (Figure 22 and Figure 29). However, many shortfalls remain under RCP 4.5 and RCP 8.5 (Figure 29b and Figure 29c, respectively). In the context of this project, a limited number of adaptation measures were tested. In the follow-up to the project, if there remains shortfalls once all conceivable adaptation measures have been tested and the best measures have been retained, the only means of stabilizing timber supply would be to decrease harvest rates over time, in a manner similar to the "fall-down effect" in British Columbia. This approach could allow for a gradual transition from the current climate to a future climate less conducive to forestry.

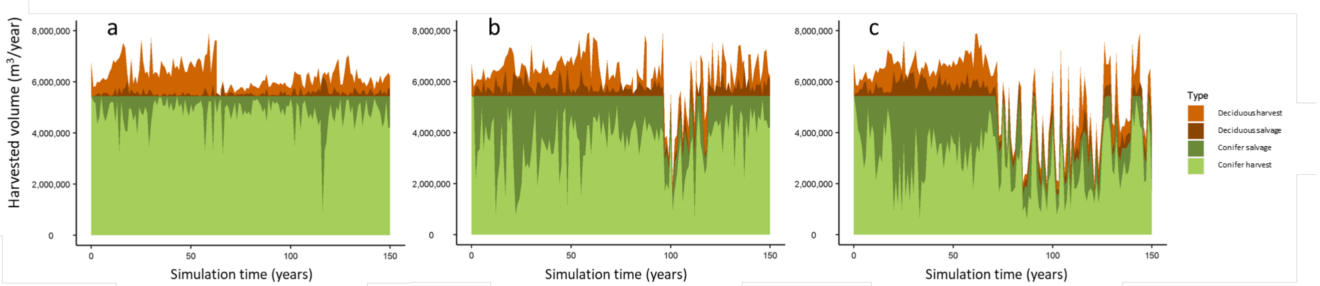


Figure 29. Harvested volumes under the Intensive_F50_Plant2 adaptation scenario, under (a) historical, (b) RCP 4.5, and (c) RCP 8.5 climate scenarios. The targeted harvest level in all cases is the maximum sustained yield harvest level under the historical climate; for these scenarios, the model allows shortfalls if the harvest target cannot be reached.

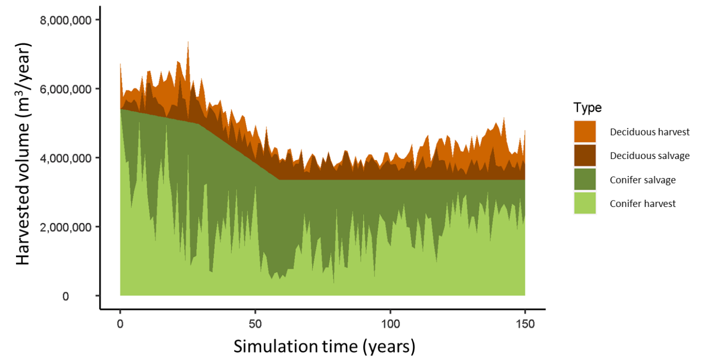


Figure 30. Adjustment of harvest rates over time, seeking to stabilize timber supply over the long term. These results were obtained with the Intensive_F50_Plant2 adaptation scenarios under the RCP 8.5 climate scenario.

4.2. Decision support

Through the decision-support process, modeling results were synthesized and could help to shed light on the choices to be made for the future. The results presented herein apply only to the adaptation measures tested in the context of this project and will change as new measures are tested with the model.

4.2.1. Comparison of adaptation scenarios

4.2.1.1. Sensitivity of the old forest and caribou disturbance rate indicators

Among the indicators selected for decision support, two indicators showed little sensitivity to the adaptation measures and management scenarios tested under climate change.

The disturbance rate of woodland caribou habitat appears to increase under the RCP 4.5 and RCP 8.5 climate scenarios, both without forest management and under the status quo management scenario. The reason the disturbance rates are lower for RCP 4.5 and RCP 8.5 compared to the status quo history is that the maximum sustained yield harvest levels are lower under the climate change scenarios. Only the historic climate without forest management scenario sees an improvement in woodland caribou habitat (Figure 31). Under climate change scenarios, the mean age of the forest decreases (Figure 12 and Figure 20), which leads to an increase in the caribou habitat disturbance rate.

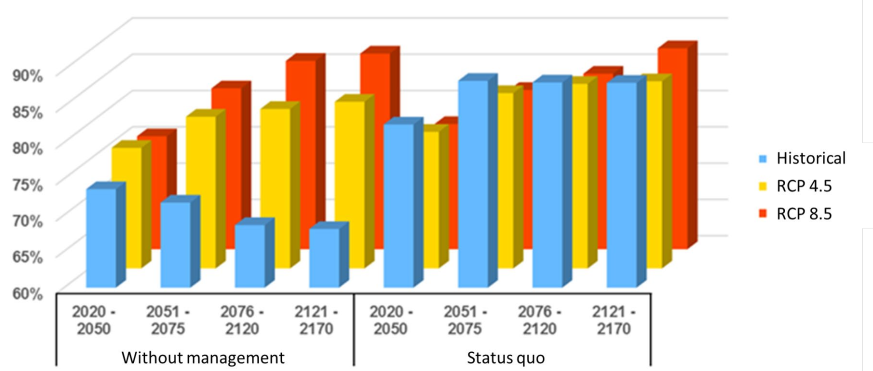


Figure 31. Comparison of caribou disturbance rates in the caribou range that intersects with the management forest of the study area, for the status quo scenario and scenario without forest management.

Regeneration failure significantly modifies the forest and has an impact on the proportion of old forests in the region. Although the old forest targets are maintained for the status quo scenario, the amount of old forests decreases significantly throughout the region (Figure 12 and Figure 20) under climate change. Under climate change assumptions, the percentage of old forests decreases under both the “without management” and status quo management scenarios. The proportion of old forests increases within the region under the historical climate and without management scenario (Figure 32).

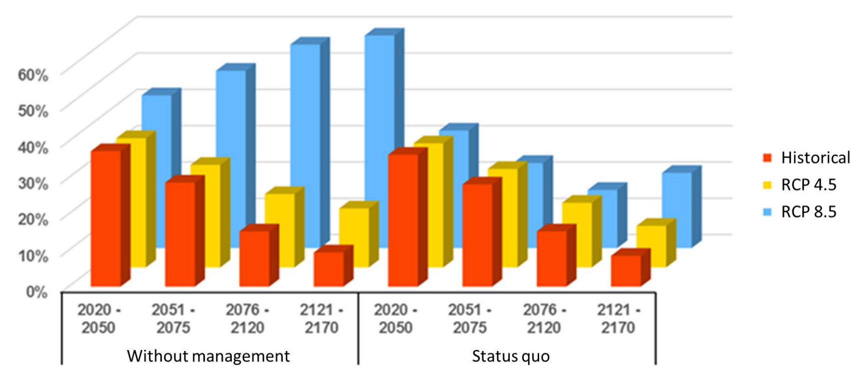


Figure 32. Comparison of the proportion of old forest in the study area, for the status quo scenario and scenario without forest management.

To allow a better synthesis of results, the caribou disturbance rate and old forest indicators were not included in the decision support tool due to their low sensitivity to adaptation measures. Under the adaptation measures tested, these indicators were found to be non-discriminating. However, in the future, they should be kept because an adaptation measure could demonstrate an improvement in their condition. They remain present in the model as tracking variables.

4.2.1.2. Evaluation matrix

The evaluation matrix created from modelling results is presented in Table 18. This table presents only the indicators identified as being important. For the sake of illustration, intervals applied by the project team are used to identify the degree of acceptability of the adaptation scenarios tested. These intervals could have been different and include a degree of subjectivity. Ideally, these acceptability intervals should be established in a consensual manner by the decision makers involved.

Interpretation of the matrix suggests that the adaptation scenarios assessed under climate change would not maintain indicators within their historical range of variability. However, the matrix indicates that the most intensive adaptation measures would keep harvest levels within an acceptable range, based on the intervals established, under RCP 4.5. The salvage effort and the amount of planting required by adaptation scenarios suggest that the search for more effective adaptation measures should continue.

Depending on the number of adaptation scenarios and indicators included, the evaluation matrix could quickly become too complex to read. This complexity led to the development of another method to compare results: the analysis of trade-offs among the different scenarios according to indicator-related objectives (section 4.2.2).

Table 18. Evaluation matrix integrating intervals for preference (in green), discomfort (in yellow), and rejection (in red).

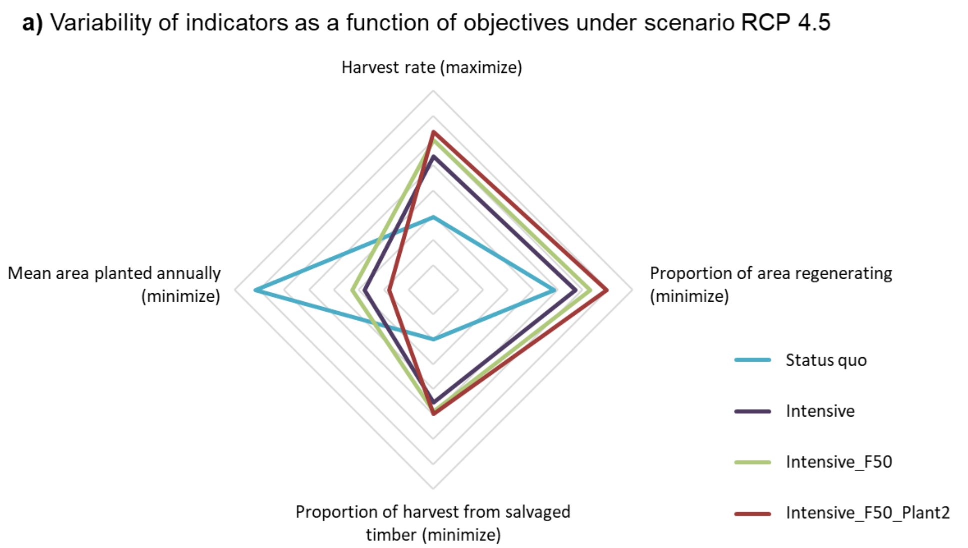
Scenarios	Indicators and periods	Mean harvest rate (m^3/year)			Percentage of forest in regeneration failure (%)			Portion of harvested volume from salvage (%)			Mean annual area planted (ha)		
	RCP	Historical	RCP 4.5	RCP 8.5	Historical	RCP 4.5	RCP 8.5	Historical	RCP 4.5	RCP 8.5	Historical	RCP 4.5	RCP 8.5
Status quo	2020 - 2050	6 240 704	3 685 506	2 077 021	1%	4%	3%	12%	71%	84%	17 945	19 021	18 658
	2051 - 2075	7 140 787	3 794 267	2 181 075	1%	10%	11%	8%	82%	83%	15 629	20 100	20 100
	2076 - 2120	6 611 750	4 014 877	2 288 178	2%	19%	25%	9%	67%	79%	14 395	20 100	20 100
	2121 - 2170	6 528 624	4 267 888	2 496 041	3%	28%	38%	11%	38%	58%	15 713	20 100	20 100
Intensive	2020 - 2050	7 631 472	5 556 630	3 060 931	0%	2%	2%	11%	44%	78%	38 259	51 836	36 851
	2051 - 2075	8 313 743	5 513 926	3 234 274	0%	7%	8%	7%	54%	81%	26 117	44 181	50 653
	2076 - 2120	7 075 474	5 360 662	3 199 945	1%	14%	19%	7%	36%	74%	29 753	47 587	56 719
	2121 - 2170	7 162 519	5 635 537	3 197 532	1%	21%	29%	13%	26%	49%	28 195	45 420	52 533
Intensive_F50	2020 - 2050	7 500 692	5 888 581	3 820 348	0%	2%	2%	11%	47%	68%	37 564	46 651	40 075
	2051 - 2075	8 211 570	5 903 769	3 995 346	1%	7%	7%	7%	44%	82%	26 196	41 271	52 662
	2076 - 2120	7 072 322	5 761 068	3 955 604	1%	11%	14%	7%	32%	65%	27 883	47 366	54 751
	2121 - 2170	7 314 333	6 168 369	4 107 319	1%	13%	18%	12%	22%	32%	28 154	41 798	51 292
Intensive_F50 _Plant2	2020 - 2050	7 620 185	5 967 500	3 910 841	0%	1%	1%	12%	42%	68%	44 272	58 057	54 003
	2051 - 2075	8 326 704	6 035 906	4 139 909	0%	5%	3%	6%	44%	80%	32 339	57 189	57 535
	2076 - 2120	7 148 825	6 058 382	4 083 925	0%	7%	8%	7%	30%	66%	31 317	51 246	64 702
	2121 - 2170	7 492 227	6 487 404	4 367 095	0%	8%	10%	11%	25%	33%	31 101	47 432	53 430
Intervals	Preference		greater than 6.0 M (+/- 5%)			less than 3%			less than 10%			less than 35000	
	Discomfort		5.5 to 5.9 M (+/- 10%)			3 to 5 %			10 to 25 %			35000 to 40000	
	Rejection		less than 5.5 M			greater than 5%			greater than 25 %			greater than 40000	

4.2.2. Analysis of trade-offs among different adaptation scenarios

The results of adaptation scenarios under RCP 4.5 (Figure 33a) and RCP 8.5 (Figure 33b) for each indicator rank roughly in the same order for each adaptation scenario. The difference being that RCP 8.5 makes the attainment of objectives, as measured by each indicator, more difficult.

The adaptation scenario that maximizes harvest levels over the entire planning horizon, the Intensive_F50_Plant2, is the scenario that requires the greatest planting effort (Figure 33a and Figure 33b). This result suggests that such a scenario may be unrealistic since, as compared to the status quo scenario where the planting target represents what is currently being done in the region, the area planted is significantly higher, which runs counter to the objective of minimizing planted area.

The scenarios involving the most enrichment with hardwoods led to a reduction in the percentage of forest area where regeneration fails, thus improving the objective of minimizing regeneration failure. Finally, in the intensive management scenarios, the proportion of the harvest as salvaged timber is less than under the status quo scenario.



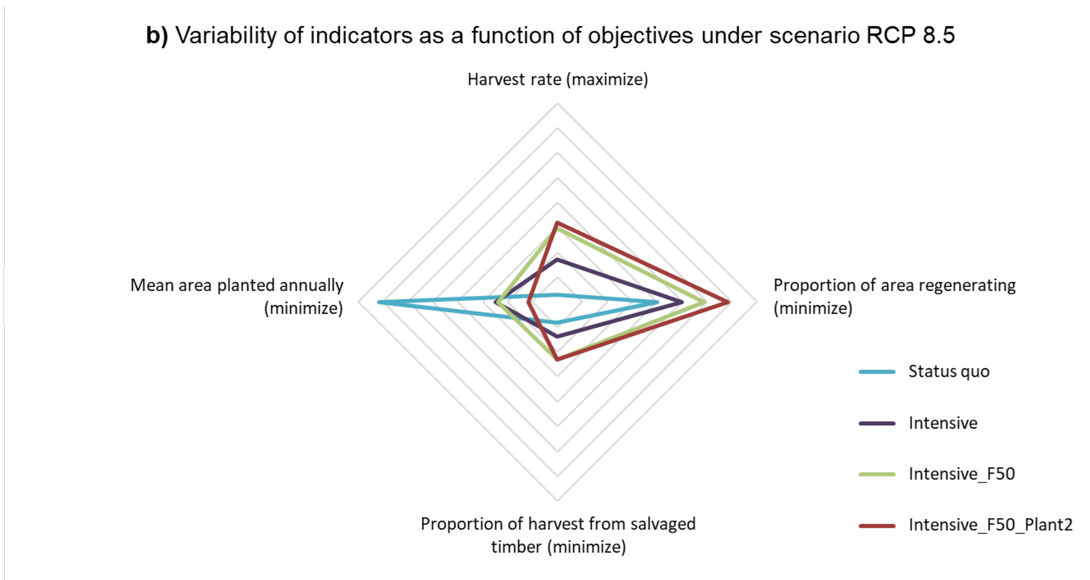


Figure 33. Variation of indicators according to the adaptation scenarios tested under (a) RCP 4.5 and (b) RCP 8.5.

4.2.3. Ranking adaptation scenarios

Because a multi-criteria aggregation method suited to the project's context was not available, a simple aggregation procedure was developed. The procedure involved assigning a score to each indicator value (section 3.3.2.5), by climate scenario and by time period, on each adaptation scenario (Table 19). The weights on every indicator and time period were equal for the purpose of the exercise.

Interpretation of these results shows that the two most intensive adaptation scenarios give fairly similar results in terms of their respective scores. Since a perfect overall score would be 16, it can be concluded that none of the scenarios tested performs best over all indicators. A compromise would therefore be necessary to be able to retain a single scenario.

Table 19. Scores for adaptation scenarios according to climate scenario and time period.

Scenarios	Time period	RCP 4.5						RCP 8.5					
		Harvest rate	Regeneration failure	% salvaged volume	Annual plantation	Score for time period	Score for scenario	Harvest rate	Regeneration failure	% salvaged volume	Annual plantation	Score for time period	Score for scenario
Status quo	2020 - 2050	4	2	3	1	10	45	3	2	3	1	9	41
	2051 - 2075	4	3	3	1	11		4	3	1	1	9	
	2076 - 2120	4	4	3	1	12		3	4	3	1	11	
	2121 - 2170	4	4	3	1	12		4	4	3	1	12	
Intensive	2020 - 2050	3	1	1	3	8	39	2	1	2	2	7	35
	2051 - 2075	3	2	2	3	10		3	2	1	2	8	
	2076 - 2120	3	3	2	2	10		2	3	2	3	10	
	2121 - 2170	3	3	2	3	11		3	3	2	2	10	
Intensive_F50	2020 - 2050	2	1	2	2	7	28	1	1	1	3	6	27
	2051 - 2075	2	2	1	2	7		2	2	1	3	8	
	2076 - 2120	2	2	1	2	7		1	2	1	2	6	
	2121 - 2170	2	2	1	2	7		2	2	1	2	7	
Intensive_F50_Plant2	2020 - 2050	1	1	1	4	7	27	1	1	1	4	7	26
	2051 - 2075	1	1	1	4	7		1	1	1	4	7	
	2076 - 2120	1	1	1	3	6		1	1	1	4	7	
	2121 - 2170	1	1	1	4	7		1	1	1	2	5	

Table 20 shows the range of variability of the indicators, by climate scenario and adaptation scenario. This table combined with the scoring of scenarios can help inform decision makers about the most efficient scenario and the potential impacts of climate change.

Table 20. Variability of indicators according to climate and adaptation scenario.

Adaptation scenarios	Climate scenarios	Harvest rate		Regeneration failure		% salvaged volume		Annual plantation	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Status quo	Historical	6 240 704	7 140 787	1%	3%	8%	12%	14 395	17 945
	RCP 4.5	3 685 506	4 267 888	4%	28%	38%	82%	19 021	20 100
	RCP 8.5	2 077 021	2 496 041	3%	38%	58%	84%	18 658	20 100
Intensive	Historical	7 075 474	8 313 743	0%	1%	7%	13%	26 117	38 259
	RCP 4.5	5 360 662	5 635 537	2%	21%	26%	54%	44 181	51 836
	RCP 8.5	3 060 931	3 234 274	2%	29%	49%	81%	36 851	56 719
Intensive_F50	Historical	7 072 322	8 211 570	0%	1%	7%	12%	26 196	37 564
	RCP 4.5	5 761 068	6 168 369	2%	13%	22%	47%	41 271	47 366
	RCP 8.5	3 820 348	4 107 319	2%	18%	32%	82%	40 075	54 751
Intensive_F50_Plant2	Historical	7 148 825	8 326 704	0%	0%	6%	12%	31 101	44 272
	RCP 4.5	5 967 500	6 487 404	1%	8%	25%	44%	47 432	58 057
	RCP 8.5	3 910 841	4 367 095	1%	10%	33%	80%	53 430	64 702

4.3. Taking into account and integrating different points of view in the project

The context of this project differs significantly from real-world decision making contexts. When the future of a collective good, such as forests on crown land and the environmental services it provides to society, is under consideration the scope of decision-making – whether it is strategic, tactical, or operational – is of great importance. Indeed, when a region[18] wishes to implement a management strategy that seeks to adapt to future climate conditions, the region becomes an essential party to the process. Likewise, other regional actors, such as the forest industry, the municipal sector, and government officials – in particular those who allocate funds or whose

[18] TN: In Quebec, forest management planning is developed by administrative region.

work is otherwise affected by decision, such as for forest protection or the production of seedlings for reforestation – should be part of the process from the start of the work. This is essential for concerned parties to take ownership of scenarios and associated risks and for the development of a shared vision. The same applies to the social acceptability of actions that could be implemented.

As part of the project, managers from the region were involved, but in a limited way. They had the opportunity to express their expectations and concerns, and these were incorporated as much as possible. However, it was observed that the level of perception as to the scope of the project was different. Indeed, the project was carried out from a long-term strategic planning perspective, whereas the legitimate concerns of managers were more often of a tactical and operational nature.

The level of involvement of various decision makers in such a project is not uniform. Participation could be structured according to the degree of responsibility at the strategic, tactical and operational levels and broadened for follow-up work.

4.4. Strengths and limits to interpretation

The work presented in this report represents important advances in the integration of climate change into the determination of allowable cut. However, it is important to underline the limits to the interpretation of the results of this work. This project was designed to develop an approach and a model; the strengths and limitations underscore the importance of possible future developments.

4.4.1. Strengths

Certain aspects of the project represent important developments for decision support in a context of sustainable forest management, most notably:

- An integration of climate change to the modelling of forest management at the Office of the Chief Forester
- The integration of many natural disturbance types and forest management within one model
- The ability to test adaptation measures
- The development of a decision support tool, run in parallel to the development of a simulation model
- An integration of the Chief Forester's databases to the simulation of impacts and adaptations to climate change
- A consideration for uncertainty, through the inclusion of three climate scenarios
- An identification of potential major challenges to forestry for the region under climate change:
    - The impact of wildfire on the forest,
    - Regeneration failure and loss of productive forest area,
    - A drop in productivity for certain species in the region over the long-term, and
    - The degree of misadaptation of the current regional management strategy, given expected climate change.
- An identification of knowledge gaps.

4.4.2. Limits to interpretation

Along with the important developments required as follow-up to the project, limits to the interpretation of project results must be underlined. The project represents a first attempt at modeling the impacts of climate change at the Office of the Chief Forester. This first attempt allowed an exploration of the subject and generated much learning. The results presented in this report should not be used to inform forest managers about immediate actions to be taken in the field. The approach will need to be developed further, for example by testing a larger number of adaptation measures and by pursuing the potential developments identified in this report (section 5), before a contribution to decision-making in forest management, both at the operational and strategic level, is possible. Also, results suggest that significant effort will need to be made on the part of government authorities and forest sector stakeholders to seek the best possible management scenarios to ensure the resilience of the forest in the face of climate change in the Saguenay – Lac-Saint-Jean area. Beyond the exploratory nature of the project, the following factors limit the scope of conclusions that can be drawn from the results:

- Many elements were not taken into account, such as management constraints other than old forests, defoliating insects other than spruce budworm, windthrow, pathogens of trees, and invasive species;
- In many cases, such as with fires and spruce budworm, only one source of scientific knowledge was integrated into the model; triangulation using multiple sources of knowledge is needed;
- The operational and financial feasibility of the adaptation measures included in management scenarios was not tested;
- The process was developed for only one region;
- A limited number of adaptation measures were tested; and
- The model applies a limited number of silvicultural treatments.

5. Perspectives

Within the framework of this project, the intention was not to solve all of the challenges raised by the modeling results. Rather, the intention was to attempt, for the first time, to design a process that will eventually support annual allowable cut determinations by estimating the potential impacts of climate change and natural disturbances on forests. Being a first attempt, several avenues of development have been identified. The following sections highlight the developments that will fuel continuous improvements to the work undertaken on the integration of climate change and natural disturbances to the determination of allowable cuts.

5.1. Overarching elements

For the follow up work to this project, it will be important to better integrate uncertainty into the analysis. The project was able to include the uncertainty associated to future climates by integrating three climate scenarios, but a more complete integration of the uncertainty related to certain factors, such as the variability of fires on a regional scale, will provide a more complete picture of the risks and vulnerabilities associated with natural disturbances and climate change.

Having better integrated the various sources of uncertainty, the necessarily broader ranges of responses to disturbance and climate change will need to be integrated into the decision support process. Financial analysis that seeks to support decision making in the face of market volatility and longer-term uncertainty promises to provide useful leads. Financial analysis would also allow a structured evaluation of the costs and benefits associated with the different management strategies, including those generated by different adaptation measures under climate change.

In order to properly align future developments with research on the subject and ensure consistency with management strategies, it will be necessary to collaborate with other sectors within the Ministry of Forests, Wildlife and Parks, while maintaining partnerships with various researchers in their respective fields.

To export the approach developed by this project to the other regions of Quebec, the processes specific to the deciduous forest will need to be integrated, since the dynamics of this forest are fundamentally different from those of the boreal forest. The distinctness of these processes stems from the nature of these ecosystems (deciduous species, gap dynamics), their management (e.g., partial harvests, progressive harvests, commercial thinning), and the natural disturbances to which they are subject (e.g., windfall, pest insects specific to deciduous forests, and diseases such as beech bark disease).

5.2. Decision support

In the field of decision science, an evaluation of existing aggregation procedures will be necessary to account for both time and uncertainty through the synthesis of a large amount of information.

Significant methodological development should also be expected in order to include the preference systems of a broader range of decision-makers, such as regional planners, in order to allow collaborative decision making. Buy in to the approach by all decision-makers should be sought.

5.3. Wildfire

As wildfires proved to be of great importance in this project, this aspect of the modeling should be developed further. The following elements could be developed in the follow up work:

- The creation of multiple fire sequence replicates that respect the spatial scales at which the fire data was generated and then applied in the context of modelling;
- The further development of fire initiation probability maps as a function of historical fires, but also as a function of topography, regional climatic patterns, and human infrastructure;
- An integration of the effects of the spatial configuration of fuels on the fire regime;
- An integration of fire control effort into the modelling;
- A modulation of stand regeneration and salvage logging as a function of fire severity; and
- A diversification of sources of information for the effect of climate change on fire regimes.

5.4. Forest management

There are many avenues of development related to forest management:

- The development of new adaptation measures (e.g., the creation of new strata for ligniculture, the plantation of conifer species that exhibit more precocious reproductive maturity);
- Refinement of the spatial distribution of forest management actions to improve the response of indicators;
- Integration of partial harvesting and other treatments applied in the mixed and deciduous forests;
- Refinement of climate change effects on salvage logging (e.g., longhorned beetles);
- Implementation of solutions obtained through optimization in Woodstock[19] into the BFEC-CC model;
- Improvement of the modelling of roads and access to the region's forests; and
- Development of intensive management measures collaboratively with regional planners.

5.5. Regeneration / species distribution

Regeneration failures proved to be of great importance to the project's results. Adaptation measures leading to an enrichment in deciduous species generated interesting results, notably for its role in controlling regeneration failure.

Assisted migration, for which little empirical data was available at the time the model was developed, should be examined and integrated to this work to help maintain productive forest area.

Also, it will be helpful to improve the modeling of natural regeneration through the integration of (i) seed dispersal into disturbed area, (ii) the effect of climate change on the establishment of seedlings, and (iii) the effect of salvage logging on regeneration by seed.

To better take into account the effect of site productivity (which can be expected to change under climate change) on seed production, criteria to determine reproductive maturity based on stand growth could be implemented.

In the modeling developed for the project, forest succession is not directly affected by climate. It will be pertinent to make forest succession sensitive to climatic conditions in follow up work.

[19] Woodstock is a modelling tool created by Remsoft Inc. that allows the user to apply linear programming to forest management.

5.6. Defoliating insects and pathogens

As implemented in this project's modelling, defoliation by insects is relatively simple; only one insect, the spruce budworm, was modeled and only the effect of severe defoliation leading to a stand replacing disturbance was included. For the work to follow, other effects of budworm outbreaks (for example, on the flammability and productivity of stands) as well as other insect pests and pathogens could be included in the modeling.

5.7. Productivity

In an associated project, a limited number of species were included in the modeling of the impact of climate change on forest productivity (Power and Auger, 2019). In order to study the effect of climate change on other regions and to allow the migration of species, it will become necessary to model the productivity of additional species under climate change. It will also be necessary to refine the modeling of mortality and recruitment within the framework of these models. The prediction of the number and species of new seedlings replacing cut trees in the stand will need to be climate sensitive.

As water deficits could be of great importance to the region in the future, it will be useful to integrate the effects of drought on tree growth and mortality.

6. Exporting the model to other regions

In its current state, the BFEC-CC model could be exported to other boreal regions of Quebec (Abitibi-Témiscamingue, Nord-du-Québec and Côte-Nord) by updating the initial forest inventory, forest strata, and region-specific management strategies. The adjustments required to export the model elsewhere in Quebec and to other Canadian provinces have been identified. Some elements of the model could be exported in their current state (section 6.1), while other elements will need to be adapted or replaced (section 6.2).

6.1. Elements that can be exported in their current state

The following elements could be exported, regardless of context:

- The iterative approach to learning and the development of scenarios (section 3.3)
- The approach to decision support
- The general framework for the modelling of management strata
- The system to transition strata following disturbance, and
- For ecosystems where fire is present: the modelling of fire under many different climate scenarios.

6.2. Elements that should be adapted or replaced

The following elements will need to be modified or replaced in order to generate interpretable results in other contexts:

- Natural disturbance types (e.g., windthrow, insects other than budworm, disease)
- Forest harvesting (additional treatments such as partial cutting, selection cutting, shelterwood cutting)
- Other silvicultural treatments (e.g., commercial thinning, variable retention)
- Merchantable volume tables, by species groups
- Post-disturbance transitions, and
- The indicators associated with local issues.

Development is under way to extend the modelling of climate change impacts and adaptations to all of Quebec's forests.

Conclusion

The project has demonstrated that it is possible to model interactions between the future climate and forest management at a regional scale. Up-to-date scientific knowledge and the collaboration of project partners were essential to its realization. In addition to identifying certain risks for the forests of the Saguenay – Lac-Saint-Jean region, certain potential adaptation measures have been identified and tested. The approach developed contributes to the decision-making process through a synthesis of modelling results. Further developments will be necessary to ensure that the decision support process can evolve along with the model and help to inform a broader group of contributors to decision-making.

It should be reiterated that the objective of this project was to develop an approach to modeling that could take into account the uncertainty related to climate change in the context of allowable cut determination in Quebec. The project made it possible to integrate a range of processes into one model (forest management, fires, the spruce budworm, stand productivity, and regeneration failures) and to assess the interactions among these different processes in a context of climate change.

In addition, learning on a broad range of topics emerged in relation to modeling, the impacts of climate change on forest management, the sensitivity of the model to certain adaptation measures, and the decision-making process. This project concerns a single region of Quebec; the results cannot be transposed directly to other regions without repeating the exercise with the model. The sources of scientific knowledge need to be broadened, because for certain modeled processes only one scientific source was used.

For the Saguenay – Lac-Saint-Jean region, given modelling assumptions, results suggest that the forest of tomorrow will be different from that of today. Shorter fire cycles are to be expected and could result in a significant loss of productive forest area. Although increased growth of conifer and deciduous species is expected under certain conditions, this increase is not expected to offset the effect of fires on long-term allowable cuts, underscoring the need to develop efficient adaptation measures.

Furthermore, the results obtained stimulate more general thinking on the manner in which forest management is carried out, and on the future of forests and the environmental services that they provide to society. Questions were raised with regards to the compromises to be made to ensure the maintenance of old-growth forests that have a high probability of burning. Facilitation of discussions on values with the stakeholders will have to be undertaken in order to ensure an acceptable future. Given the results presented, it is conceivable that the structure and dynamics of the forest will change under climate change, and adaptation with regards to forest practices will be needed.

For example, increasing the proportion of deciduous trees in the forest would reduce the flammability of the forest, but would make a conifer dominated forest into a deciduous one, requiring significant adaptation by the forest industry which would no longer have access to the timber supply to which it is accustomed.

Additionally, land-based forest fire control and the large-scale recovery of salvageable volumes depend on the maintenance of sustained access to the forest through an adequately developed road network. However, such a network is not desirable in the context of woodland caribou habitat protection.

In such a context, maintaining the current management strategy under climate change may lead to unacceptable forest conditions with regards to the sustainability of the forest resource. Although the results of certain adaptation measures – such as the intensification of management and enrichment in deciduous species – demonstrate that it is possible to mitigate the impacts of climate change, actions must be taken today to ensure that the forest of the future meets the expectations of the people of Quebec. We must therefore collaboratively define a vision for the forest of tomorrow and act accordingly without delay.

At the same time, it will be necessary to expand our understanding of the impacts of climate change and to integrate this knowledge into modeling in order to produce a clearer picture of the future. The role that assisted migration can play in a context of adaptation will need to be better understood and tested in the field. The effect of existing and innovative silvicultural treatments under climate change should also be explored. The deciduous forest, with its own dynamics and silvicultural treatments, must also be integrated into the process. The effect of spatial context on the initiation and propagation of fires will need to be better understood and integrated into the modeling. The uncertainty associated to the stochasticity of natural and anthropogenic disturbances and the inclusion of multiple decision makers will also need to be integrated into the decision support process. In the follow up to the project, it will be important to continue to develop and test various adaptation measures in collaboration with forest management planners in the Saguenay – Lac-Saint-Jean region, while generalizing the model to the other regions of Quebec.

Finally, the results underscore the importance of maintaining efforts to mitigate greenhouse gas emissions, because the results of simulations under the RCP 8.5 scenario show a situation in which it will be difficult to sustain the forest and all ecosystem services that it produces, carbon storage among them. Indeed, significant losses of productive forest area, as shown in the results, suggest that carbon sequestration in forests may be diminished under climate change.

Recommendation

The Chief Forester recommends collaboration on research and development efforts among the various stakeholders, practitioners, and researchers in the field – both within the Ministry of Forests, Wildlife and Parks and externally – to facilitate the development of innovative solutions to adapt the forest, the forestry environment, and forestry practices to climate change. This collaboration could save time during the implementation phase of new strategies, and could also lead to greater efficiency if research efforts are well coordinated. The Chief Forester will continue to integrate this new knowledge into ongoing work.

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Annex: List of BFEC-CC model outputs

The following table presents the output files of the BFEC-CC model, as well as a brief description of their contents.

File name	Information contained in the output
ageClassArea.txt	Area (ha) by 5 year age classes
ageClassArea2.txt	Area (ha) by zone, where age is equal to or greater than 50 years
ageClassVol.txt	Volume (m^3) by 5 year age classes
allZonesByAuReport.txt	Report, by UTA, on the (old forest and disturbance rates) constraints, whether they are in effect or not
allZonesReport.txt	Yearly summary of key constraints and harvest rates
areaByConstraint.txt	By management unit, the area (ha) in different availability classes (available, salvageable, too young)
availVolByConstraint.txt	Details on standing green timber
BernierClasses.txt	Area (ha) by composition and age class according to the Bernier et al. (2016) classes
BernierParam.txt	Bernier parameters applied in the modelling
BurnRecord.txt	Area burned (ha)
CaribouRecord.txt	Area as caribou habitat (ha)
EpcRecord.txt	Annual area as pre-commercial thinning (ha)
FireSizeRecord.txt	Fire size distribution (ha/class)
HarvestRecord.txt	Harvested area and volumes, by type of volume
IntensiveRecord.txt	Area planted in intensive management zones (ha)
KeyOutput.txt	Summary of key indicators
LinearRecord.txt	Area occupied by linear features (ha)
LostVolBurn.txt	Volumes lost to wildfire (m^3)
LostVolDecay.txt	Volumes lost to degradation after fire (m^3)
ManagementIntensity.txt	Management intensity indicators (ha by intensity class)
PlantedStrataRecord.txt	Area planted by strata (ha)
PlantRecord.txt	Area planted (ha)
RegenRecord.txt	Regeneration failure outputs
RoadsRecord.txt	Area occupied by roads, by road class (ha)
SalvageRecord.txt	Salvaged area and volumes (ha)
strataArea.txt	Area by strata (ha)
strataVol.txt	Volumes by strata (m^3)
tbeMortalite.txt	Area of severe mortality (ha)
volModAreaWeight.txt	Annual summary of CC volume modifiers
volumeByConstraint.txt	Merchantable volume by availability class (m^3)
zonesAUReport.txt	Indicators by UTA
zonesReport.txt	Indicators by zone type

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