TITLE PAGE

Title: Response of forest productivity to changes in growth and fire regime due to climate change

Running Title: Climate change and boreal forests productivity

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ABSTRACT

Climate change is having complex impacts on the boreal forest, modulating both tree growth limiting factors and fire regime. However, these aspects are usually projected independently when estimating climate change effect on the boreal forest. Using a combination of 3 different methods, our goal is to assess the combined impact of changes in growth and fire regime due to climate change on the timber supply at the transitions from closed to open boreal coniferous forests in Québec, Canada. In order to identify the areas that are likely to be the most sensitive to climate change, we projected climate-induced impacts on growth and fire activity at three different time periods: 2011-2040 RCP 8.5 for low growth change and minimum fire activity, 2071-2100 RCP 4.5 for moderate growth change and medium fire activity, and 2071-2100 RCP 8.5 for high growth change and maximum fire activity. Our study shows the importance of incorporating fire in strategic forest management planning especially in a context of climate change. Under the most extreme scenarios the negative impact of fire activity on productive area and total volume mostly offsets the positive effects of climate change via improved tree growth.

Keywords: boreal forests; climate change; productivity; growth; fire regime

RÉSUMÉ

Le changement climatique a des impacts complexes sur la forêt boréale, modulant à la fois les facteurs limitant la croissance des arbres et le régime des feux. Cependant, ces derniers sont généralement projetés indépendamment lors de l'étude de l'effet du changement climatique sur la forêt boréale. En utilisant une combinaison de 3 méthodes différentes, notre objectif est d'évaluer l'impact combiné des changements de croissance et de régime des feux dus au changement climatique sur le stock de bois à la transition entre les forêts boréales de conifères fermées et ouvertes au Québec, Canada. Afin d'identifier les zones susceptibles d'être les plus sensibles au changement climatique, nous avons projeté les impacts induits par le climat sur la croissance et l'activité des feux à trois périodes différentes : 2011-2040 RCP 8.5, 2071-2100 RCP 4.5, et 2071-2100 RCP 8.5. Notre étude montre l'importance d'intégrer le feu dans la planification stratégique de l’aménagement forestier, en particulier dans un contexte de changement climatique. Dans les scénarios les plus extrêmes, l'impact négatif de l'activité des feux sur la superficie productive et le volume total annule en grande partie les effets positifs du changement climatique via l’amélioration de la croissance des arbres.

Mots-clés : forêts boréales ; changement climatique ; productivité ; croissance ; régime des feux

INTRODUCTION

The boreal forest is a key ecosystem on many levels (ecological, economic, cultural, etc.), particularly in Canada where the timber industry is one of the most important in the world (Burton et al. 2010). It is therefore important to manage the boreal forest in a sustainable way through ecosystem management (Gauthier et al. 2008; Gauthier et al. 2015a). With a predicted rise in global temperatures and a predicted increase in the frequency and intensity of droughts with increasing atmospheric CO_2 (Stocker et al. 2013), the boreal forest would be the forest biome most strongly affected by global warming (Price et al. 2013). In fact, an increase of mean annual temperature of 2° C and up to 6°C is projected across Canada by the end of this century, adding to an already observed increase of 1.7°C during the past century (Bush and Lemmen 2019). It can therefore be expected that continuing warming will have significant impacts on boreal forest, particularly in Canada (Gauthier et al. 2015a; Price et al. 2013).

Climate change is having complex impacts on the boreal forest, modulating both tree growth limiting factors and forest disturbances. At its northward margin in eastern Canada, many studies predict an increase in tree growth with global warming (Price et al. 2013; Girardin et al. 2016; D'Orangeville et al. 2016; Hember et al. 2017; Chaste et al. 2019; Pau et al. 2022). There, low temperatures are associated with a short growing season and nutrient-poor soil conditions, which are factors limiting growth (Jarvis and Linder 2000). Increases in temperature could have a positive effect on growth by extending the growing season and stimulating photosynthesis rates (Menzel and Fabian 1999; Chmielewski and Rötzer 2001; Menzel et al. 2006; Ibáñez et al. 2010; Price et al. 2013). On the other hand, warming and shifting water availability could cause forest losses along the warmer southern margins and within low-moisture environments, where tree growth is often limited by soil moisture availability (D'Orangeville et al. 2016; Chaste et al. 2019; Girardin et al. 2021a).

Wildfire is a major disturbance in Canada’s boreal forest, contributing to an average 2M ha of stand renewal annually (Stocks et al. 2002). Fire activity is anticipated to increase with climate change across boreal forests of Canada (Balshi et al. 2009; Wotton et al. 2010; de Groot et al. 2013; Boulanger et al. 2014; 2017; Wang et al. 2017) and may cancel out potential increase in forest stock (Gauthier et al. 2015b; Rapanoela et al. 2015; Beaudoin et al. 2017; Chaste et al. 2019). In the context of sustainable boreal forest management, it seems particularly important to assess the combined impact of climate change via growth changes and changing fire activity.

Timber supply, that we herein define as the stock of merchantable stems available for harvesting, depends on tree species growth rate and disturbance rate. In order to take into account these two factors when calculating timber supply (Savage et al. 2010; Leduc et al. 2015; Gauthier et al. 2015c), it seems important to project and combine growth changes and fire activity changes due to climate change, which few studies have yet investigated.

In this study, we investigate the response of Quebec's boreal forest timber supply, in terms of merchantable wood volume and productive area, to changes in growth and fire regime due to climate change. The goal will also be to assess which of the factors has the greatest impact on the current and future timber supply. This assessment will allow us to identify areas of the Quebec boreal forest that are likely to be the most sensitive to climate change and to assess the relevance of including fire and climate change in strategic forest management planning. This concern is particularly important in our study area, the area transition from closed to open forest forest in the coniferous boreal forest of Québec, given the socio-economic impacts associated with the Quebec boreal forest. Under current climatic conditions, the southern part of the study area, forest management is considered to be sustainable (Jobidon et al. 2015), but the effects of climate change on timber supply are still uncertain and need to be investigated (Leduc et al. 2015; Daniel et al. 2017).

To achieve this investigation, we made use of the site index (SI, height in m at 50 years) model of Pau et al. (2022) to project the direct effects of climate change on tree growth, and the fire model of Boulanger et al. (2014) to project the indirect effects via changing burn rates. The method of Gauthier et al. (2015c) and the production tables of Pothier and Savard (1998) were used to estimate mean merchantable volume and to combine the impacts of these direct and indirect effects. Since black spruce (Picea mariana (Mills.) B.S.P.) largely dominates throughout the study area, the species' timber supply was the main focus of our work. However, since jack pine (Pinus banksiana Lamb.) is a species better adapted to dry conditions than black spruce, due to its deeper root system and faster growth (Burns and Honkala 1990; Houle et al. 2014), we also wanted to determine if any advantages could be conferred by the presence of jack pine in a context of long-term exposure to increased risks of moisture deficit and wildfires.

METHODS

Study Area

Our study area extends from ~49°–53°N and ~79°–57° W in the province of Québec, Canada. This area is located at the northern limit of commercial forest (Jobidon et al. 2015), at the transition between the spruce-feather moss forest (closed forest) and the southern portion of the spruce-lichen bioclimatic domains (open forest). Beyond (northward) the northern limit, harvesting operations are absent, thus natural dynamics dominate (Jobidon et al. 2015). Black spruce is the main tree species in the area, and dominant surficial deposits are organic in western regions, deep till in central and northeastern regions, and rock in the south (Gauthier et al. 2015c). Mean annual temperature decreases from south to north (from –4.9 to 1.6 °C) and total annual precipitation increases from west to east and north to south (from 651 to 1236 mm) (Gauthier et al. 2015c). Our study area is divided into 1113 districts. A land district is defined as "an area of land characterized by a unique pattern of relief, geology, geomorphology, and regional vegetation" (Jurdant et al. 1977). At the regional level, the land district emphasizes the geographic pattern that defines certain permanent ecological aspects of the environment (Gauthier et al. 2015c; Saucier et al. 2009).

Productivity estimation

To estimate the productivity, we used the method of Gauthier et al. (2015c) based on site index (SI) and the relative density index at 100 years (RDI100). The SI, or the height at 50 years, is a commonly used temporal indicator of growth in forestry. Growth in height reflects site fertility and consequently the potential productivity of a forest stand (Monserud 1984). Given that height growth is negligibly affected by stand density (Skovsgaard and Vanclay 2008), SI mostly depends on site quality and climate being less affected by surrounding competition compared to diameter at breast height (DBH 1.3 m above ground) (Spurr and Barnes 1973). The RDI100 corresponds to "the density of a stand relative to that of a very dense stand in which all the trees are assumed to be of the same mean diameter size, normalized to 100 years" (Gauthier et al. 2015c). Given that our study area is mostly covered by black spruce, we assumed that all stands were composed only of black spruce (see Gauthier et al. 2015c). We did the same for jack pine to be able to compare the two species assuming that jack pine could be dominant in the context of long-term exposure to increased risks of water deficit and forest fires.

Forest data

Two data sets from the Gouvernement du Québec were used. To estimate productivity, we used SI and RDI100 derived from dendrometric characteristics from 9884 black spruce and 619 jack pine sample plots distributed over the entire study area. This dataset is composed in the south of sample plots from the regular Gouvernement du Québec forest survey conducted between 1990 and 2001 and in the north and east, of northern ecodendrometric northern plots surveys conducted by the Gouvernement du Québec annually from 2006 to 2009. To spatialize productivity, we used the Gouvernement du Québec detailed integrated map of forest polygons (an average of 2700 polygons larger than 4 ha for each 1114 districts over the study area). In the south, this map is composed of information acquired using aerial photographs from the third decennial forest inventory program, from 1990 to 2001, while in the north, a method based on the analysis of Landsat satellite corroborated by aerial photography (between 2005 and 2008) was adopted (Gauthier et al. 2015c; Robitaille et al. 2015).

Both datasets contain a wide variety of information on environmental and forest stands variables, such as aspect, elevation, surficial deposit, hydrologic regime, partial disturbance, ecological type, forest cover, height class, understory vegetation, and development stage. These biophysical variables were used to characterize the similarity among sites (see below in the 'Growth' section).

Climate Data

Climate data necessary to this study were obtained using the software BioSim 11 (Régnière et al. 2017). As part of the procedure, daily weather data were interpolated from Environment and Climate Change Canada's historical climate database using the four nearest weather stations to each plot, adjusted for elevation and location differentials with regional gradients. Data were used for calculation of climate normals for the 1971–2000 period and for the following variables (see Gauthier et al. (2015c) for more details): cumulative growing degree-days (°C), days in the growing season (days), consecutive days without frost (days), first frost day (Julian day), total growing season precipitation (mm), portion of total precipitation as snow (mm of water equivalent), aridity index (cm), and total radiation (MJ·m^{-2}).These variables were chosen for their impact on vegetation dynamics and growth and were also used to characterize the similarity among sites (see below in the 'Growth' section).

Growth

SI and RDI100 values were available only for our 9884 black spruce and 619 jack pine plots. As such, we used the non-parametric k-NN matching method, which consists of estimating the indices of a given polygon with the weighted mean of the indices of the *k* most similar plots (k = 13 for black spruce and k = 14 for jack pine) to assign an SI and RDI100 to each of the forest polygons using those of the plots. Climatic, environmental, and forest stand variables described above, were used to characterize the similarity between sites. The weighting of a reference plot of a target polygon is based on the inverse of the distance computed from these variables (Raulier et al. 2013). To include the uncertainty in the estimation of the SI and RDI100 of the polygons, a bootstrap resampling of *k* plots among the *k* plots used for each of the polygons was repeated 100 times to calculate productivity. Then the weighted mean of the SI and RDI100 by stand area was calculated for each of the 1113 districts.

Production classes and exposure times

Using SI and RDI100 and the production tables of Pothier and Savard (1998), Gauthier et al. (2015c) calculated the minimum age at which stands of given SI and RDI100 exceed the two-parameter productivity threshold (50 m³/ha and 70 dm³/stem), which is equivalent to exposure time to fire (Table 1). This two-parameter productivity threshold of 50 m³/ha and 70 dm³/stem correspond to a minimum operable threshold for harvesting in Quebec. The determination of this minimum harvestable limits at stand level and at stem level was based on a harvest history. These limits represent the first decile of the cumulative frequency distributions of merchantable stand and stem volumes that were harvested between 1995 and 2005 (Raulier et al. 2013) in the coniferous boreal forest of Quebec (Gauthier et al. 2015c).

Table 1. Exposure time or minimum age at which a stand of given site index (SI, height in m at 50 years) and relative density index at 100 years (RDI100) exceeds the two-parameter productivity threshold (50 m³/ha and 70 dm³/stem).

		SI											
		Black spruce						Jack pine					
		12	14	16	18	20	22	12	14	16	18	20	22
RDI100	0.1	130	110	100	95	90	90	110	90	80	75	70	70
	0.3	100	85	75	70	65	65	85	70	65	60	55	55
	0.5	90	60	50	50	45	45	130	55	45	45	40	40
	0.7	160	55	40	30	25	25	140	65	40	30	25	25
	0.9	185	70	50	40	35	30	140	95	55	40	35	30

Volume

From the SI and RDI100 and using the equations of Pothier and Savard (1998), we calculated merchantable volume (m³/ha) by district and by exposure time at 100 years.

Fire regime

Under the current climate, we defined the fire regime as in Gauthier et al. (2015c). The fire map from MFFP, based on data from aerial surveys and satellite images, was used. Data since 1972 are complete and have been subject to quality control; therefore, only the period between 1972 and 2009 was used to define the territory's current regional fire activity. Our study area is divided into 10 homogeneous fire regime (HFR) zones from Gauthier et al. (2015c) where burn rate varies between 2.272% HFR y^{-1} and 0.012% HFR y^{-1}. Indeed, HFR reflects the spatial heterogeneity of the fire regime unlike other ecological classifications (Boulanger et al. 2012). The fire regime defines the patterns of fire seasonality, frequency, size, spatial continuity, intensity, type and severity. Therefore, using a model based on HFR allows a more accurate spatial estimate of climate effects on fire regimes and thus a better projection of the future fire regime.

Based on the burn rate of each HFR, we then calculated the probability that a stand with a given SI and RDI100 would exceed the two-parameter productivity threshold while accounting for fire. The proportion of stands reaching the age where the two-parameter productivity threshold is reached is calculated using the equation of Johnson and Gutsell (1994) (Appendix 6 in Ministère des Ressources naturelles du Québec 2013):

(1)

$$Probability\ of\ exceeding\ the\ two\ parameter\ productivity\ threshold\ \ taking\ into\ account\ fires = exp(-exposure\ time\ x\ burn\ rate)$$

This gives a frequency distribution of the probability of reaching the two-parameter threshold against fire for each polygon. This procedure was repeated 10 times. Then, the weighted by stand area mean of the probabilities of exceeding the two-parameter productivity threshold taking into account fire were calculated for each district.

Productive area and total volume

We were then able to calculate the post-fire productive area as well as the total pre- and post-fire volume for each district and for each exposure time:

$$(2)\quad Post\ fire\ productive\ area = Suitable\ areas\ for\ management\ before\ fire\ x\ Probability\ of\ exceeding\ the\ two\ parameter\ productivity\ threshold$$

$$(3)\quad Total\ volume\ before\ fire = Volume\ x\ suitable\ areas\ for\ management\ before\ fire$$

$$(4)\quad Total\ volume\ after\ fire = Volume\ x\ post\ fire\ productive\ area$$

Suitable areas for management exclude areas with high physical limitations, without vegetation or considered unproductive (SI too low or negative RDI100).

Effects of climate change on growth and fire regime

To evaluate climate change impacts on forest productivity, we projected future fire regimes and tree growth according to specific future climate scenarios. We projected height growth of 9884 black spruce plots and 619 jack pine plots, and the fire regime within the 10 HFR (from Gauthier et al. (2015c)) as explained below. The same process as described above (see section Productivity estimation) was then used to extrapolate plot-level growth to district-level productivity.

Future climate projection

Our goal was to assess the combined impact of changes in growth and fire regime on the timber supply for different levels of climate change. For reference, except for 2071-2100, there is little difference in our study area between two Representative

Concentration Pathway (RCP) for the same time period. Indeed, for 2011-2040 with a 4.5 RCP, we have a projected mean temperature of 0.995 and with a 8.5 RCP, mean temperature is 1.11. Therefore, we projected climate-induced impacts on growth and fire activity at three selected periods/RCPs that seemed most relevant for our purpose: 2011-2040 RCP 8.5 for low growth change and minimum fire activity, 2071-2100 RCP 4.5 for moderate growth change and medium fire activity, and 2071-2100 RCP 8.5 for high growth change and maximum fire activity (Table 2). We used the period 1981–2010 as the reference climate (baseline). RCP scenario climate data were retrieved from the fourth generation Canadian Regional Climate Model (CanRCM4) which was driven by the second-generation Canadian Earth System Model (CanESM2)/fourth generation coupled GCM (CGCM4) to mimic 1981–2010 normals (Dunne et al., 2012). From these datasets, we then calculated future normals (30 years values) for all climate variables used by Pau et al. (2022) and Boulanger et al. (2014) models to project future growth and fire, for each of our four periods/RCPs. All climate data have been calculated with BioSim 11 (Régnière et al. 2017).

Table 2. Level of growth and fire change, their corresponding Period/RCP and their corresponding increase in mean temperature as averaged over the whole study area.

Period/RCP	Present	2011-2040 ESM2–RCP 8.5	2071-2100 ESM2–RCP 4.5	2071-2100 ESM2–RCP 8.5
Increase in mean temperature	T= 0^{o}C	+1.3^{o}C	+3.4^{o}C	+6.6^{o}C
Black spruce growth change	**No change** SI = 12.82m	**Low** +10.5%	**Moderate** +27.3%	**High** +59.7%
Jack pine growth change	**No change** SI= 13.38m	**Low** +4%	**Moderate** +17%	**High** +82.1%

Fire activity	**Current** Burn rates = 0.79% y^{-1}	**Minimum** +84%	**Medium** +326%	**Maximum** +620%

For black spruce, 20 scenarios were run to simulate independent growth or fire regime changes which allows us to see what the productivity would be if the growth or fire regime changes were over- or underestimated. For jack pine, only joint change scenarios were tested, in order to make a comparison with black spruce (Table 3).

Table 3. Climate scenarios for black spruce (BS) and jack pine (JP).

		Growth Change			
		No change	Low	Moderate	Hight
Fire activity	Without fire	BS JP	BS	BS	BS
	Current	BS JP	BS	BS	BS
	Minimum	BS	BS JP	BS	BS
	Medium	BS	BS	BS JP	BS
	Maximum	BS	BS	BS	BS JP

Climate effects on growth

To project growth change in response to climate change, we used the black spruce and jack pine growth models developed by Pau et al. (2022). Originally calibrated on data from 2591 black spruces and 890 jack pine plots using Generalized Additive Models (GAM), the formulation implements height growth based on climate normals corresponding to the growth period of each stem, and site type (as a function of texture, stoniness and drainage). With this model, we projected trends in height growth for our 9884 black spruce and 619 jack pine plots and for the future periods/RCP (Table 2).

We then estimated percent increases in height growth between future and baseline as follows:

$$(5)\ Percent\ increase\ between\ future\ and\ baseline\ (Height\ growth_{Future\ -\ baseline})$$

$$= \left(\frac{Height\ growth_{future} - Height\ growth_{baseline}}{Height\ growth_{baseline}}\right) \times 100$$

These percentage increases in height growth were then applied to our current SI, giving us a future SI for each plot and period/RCP (Table 2). In order to avoid incoherent projected SI and according to observed values and production tables of Pothier and Savard (1998), we have limited SI to a maximum value of 22 for both species.

Climate effects on fire regime

Since no models have been developed to project future burn rate within each of the 10 HFR zones developed by Gauthier et al. (2015c), we rather used models developed for Canadian-based HFR zones (Boulanger et al. 2014). These Canadian-based HFR zones were delimited at a much coarser scale and do not represent a higher hierarchical level classification of the Gauthier et al. (2015c) HFR zones. As such, we intersect both classifications and we identified which Canadian-based HFR zones pertained to each resulting portion of the Gauthier et al. (2015c) HFR zones. Future burn rate for each of these portions was then assessed by first calculating the percent change in future burn rate at the Canadian-based HFR level as follows:

$$(6)\ Percent\ change\ between\ future\ and\ baseline\ (Area\ burned_{Future\ -\ baseline})$$

$$= \left(\frac{Area\ burned_{future} - Area\ burned_{baseline}}{Area\ burned_{baseline}}\right) \times 100$$

We then weighted the percent changes for each Gauthier et al. (2015c) HFR zone according to the intersected areas, giving us a future burn rate for each HFR and period/RCP (Table 2).

Statistical Analyses

In order to evaluate which factors would be most influential on the future productivity of the study area, we realized a two-way ANOVA to determine the influence of level of change in growth and fire regime on mean merchantable volume (m^3/ha) with the 'rstatix' package in R (Kassambara 2021).

RESULTS

Both growth and fire activity significantly affected future total volume. Increasing growth with climate change is increasing total volume while concomitant increase in fire activity has the opposite effect (Figure 1). There is a significant interaction between the effects of level of growth change and the level of burn rate change on merchantable volume ($p < .0001$) (Table 4). The climate-induced effect of growth improvement fades out as fire activity conditions become more extreme. However, as growth change increases, the negative effect of burn rate change is stronger (Figure 1).

Table 4. Results from the two-way ANOVA on the influence of level of change in growth and burn rate on mean merchantable volume (m^3/ha).

Climate-induced effect	Sum of squares	Mean of squares	DF	F value	p value
Growth change	2351522	783841	3	6603.098	<.0001

Fire activity	2523996	841332	3	7087.407	<.0001
Growth change x Fire activity	33187	3687	9	31.063	<.0001

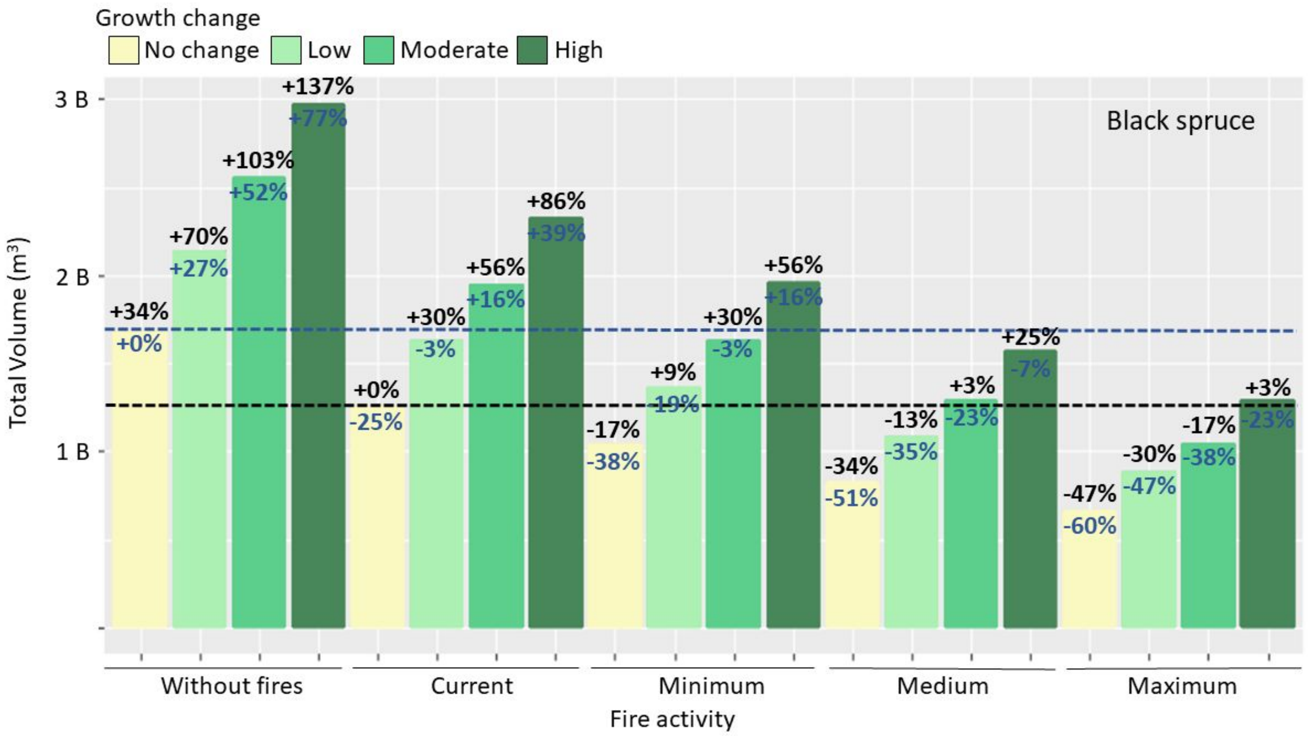

Figure 1. Projected total volume (m^3) for black spruce for four levels of change (growth/fire activity): no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5) and without fires. Percentages in blue report the changes in volume compared to no change in growth without considering fires (dotted blue line) and in black, percentage change in volume compared to no change in growth and no change in fire (dotted black line).

Omitting fire impacts would overestimate, total volume by 34% with no growth change, by +70% with low growth change, by +103% with moderate growth change and by +137% with high growth change (Figure 1). Taking into account only current fire activity would also overestimate the total volume but to a lower extent, i.e., by +30% with low growth change, by +56% with moderate growth change and by +86% with high growth change (Figure 1).

Conversely, omitting the impact of climate-induced growth change would underestimate future total volume by -17% with low growth change, by -34% with moderate growth change and by -47% with high growth change (yellow/no change bars in Figure 1).

When considering both climate-induced growth change and fire activity (i.e., same period and same RCP), there are minor differences between projected and current total volumes (Figure 1). Under joint change scenarios (same period/RCP), total volume remains similar or increases slightly and the positive effects of climate change on growth offset negative effects from changing fire regime.

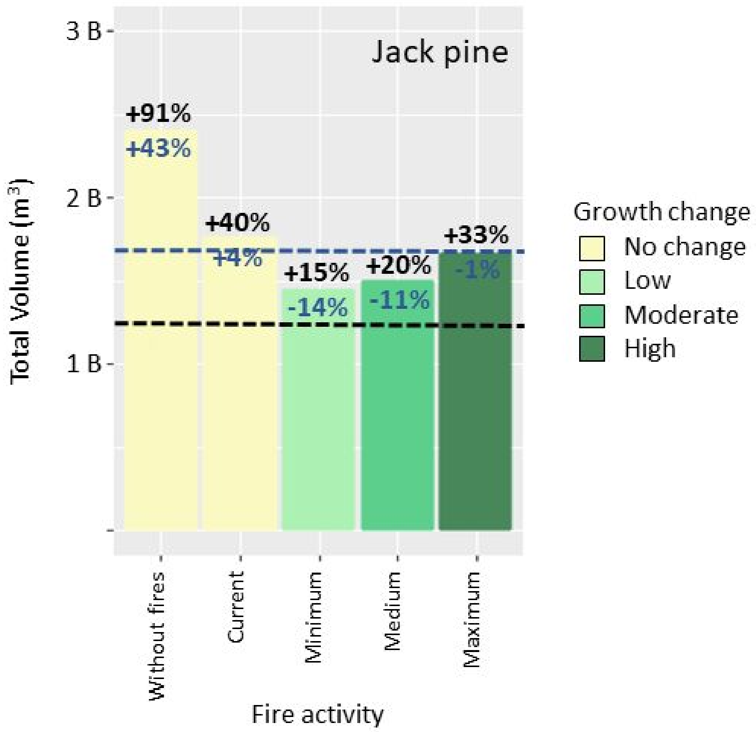

Figure 2. Projected total volume (m^3) for jack pine for four levels of change (growth/fire activity): no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5) and without fires. Percentages in blue report the changes in volume compared to no change in growth without considering fires for black spruce (dotted blue line) and in black, percentage change in volume compared to no change in growth and current fire for black spruce (dotted black line).

Compared with black spruce, jack pine total volume would be higher by +43% without fire and no growth change, by +40% with current fire activity and no growth change, by +15% with minimum fire activity and low growth change, by +20% with medium fire activity and moderate growth change, and by +33% with maximum faire activity and high growth change (Figure 2).

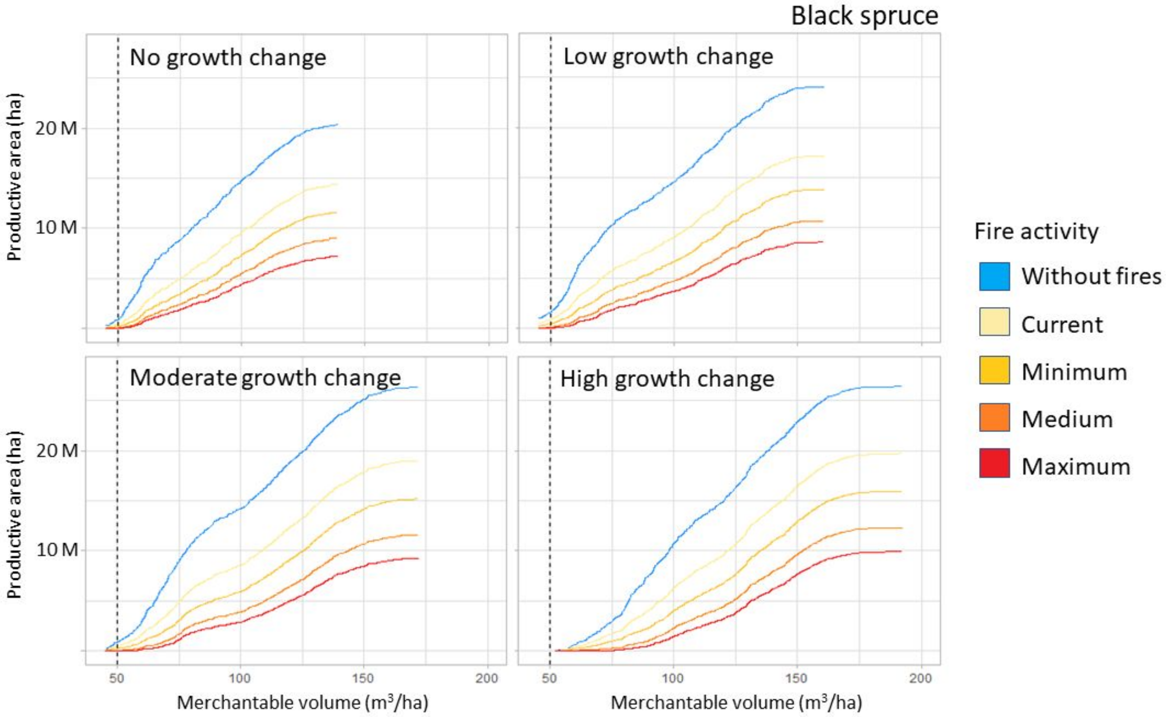

Figure 3. Projected cumulated productive area (ha) according to merchantable volume (m^3/ha) for black spruce for four levels of change (growth/fire activity): no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5) and without fires.

Again, for black spruce, omitting projected fire impacts would overestimate the productive areas by +42% with no growth change, by +74% with low growth change, by +128% with moderate growth change, and by +166% with high growth change (Figure 3). The level of change in fire regime negatively influences the productive areas while the level of change in growth positively influences both merchantable volume and available forest area (Figures 1 and 3).

Currently (no growth change and current fire activity), for black spruce, we observe a productive area of 14.3 M ha with a maximum merchantable volume of 139 m^3/ha, and half of the area exceeding 76 m^3/ha (Figure 3 top left panel). Although the productive area is greatly reduced with changes in the fire regime, the merchantable volume of the available forest area increases with changes in growth. With high growth changes and maximum fire activity, the productive area is 9.9 M ha, i.e., a decrease of -31% compared to the current situation. The maximum merchantable volume increases to 192 m^3/ha, whereas half of the productive area exceeds 121 m^3/ha.

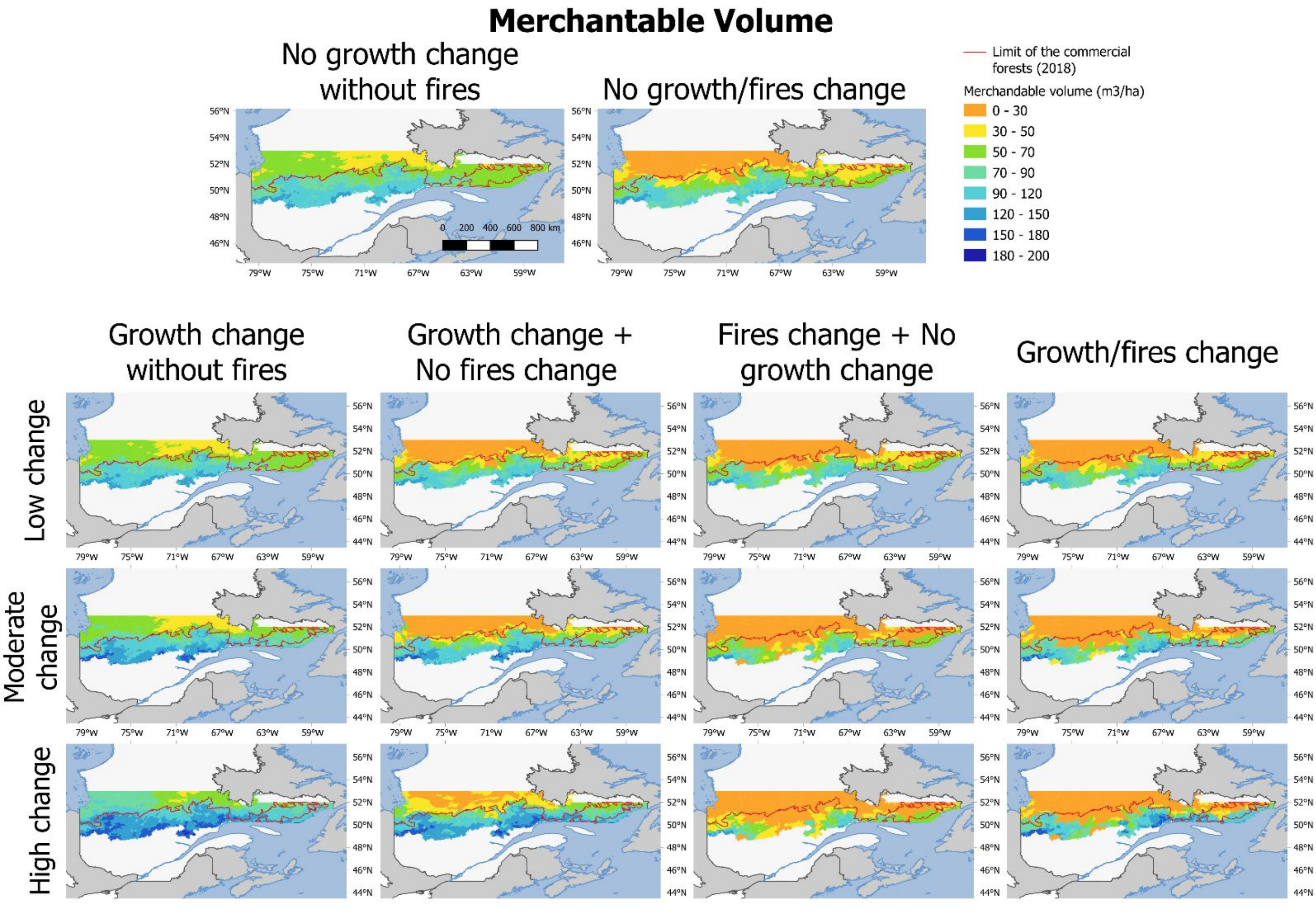

Figure 4. Projected merchantable volume (m^3/ha) (relative to the area without fire at each level of growth change) for black spruce for four levels of change: no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5),

moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5) in growth/fire activity, and without fires.

Without considering climate-induced fire and growth changes, for black spruce, most of the districts (90%) would be productive (≥ 50m^3/ha), except for a small area in the north (Figure 4 top left panel). As opposed, when the current fire regime is taken into account, the productive area is divided in two, with most of the productive area (60% of districts) being restricted to the southern part of the study area (Figure 4 top right panel).

As burn rates increase with anthropogenic climate forcing, unproductive areas increase and expand southward (Figure 4 third column panels). As the level of change in growth increases, the merchantable volume of productive areas increases (Figure 4 first and second column panels), although the area of such productive forest decreases to varying levels as a function of fire regime changes (Figure 4 fourth column panels).

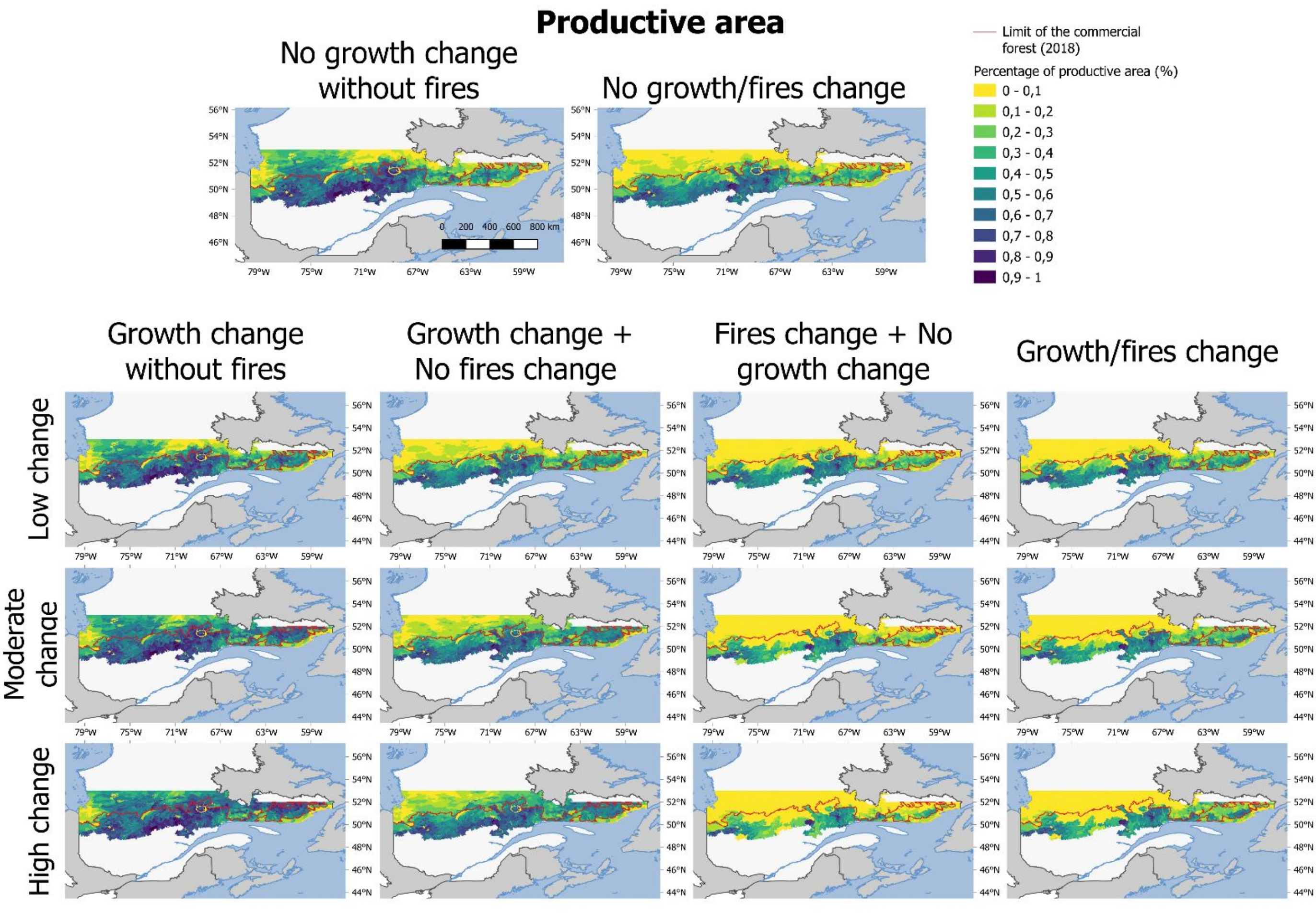

Figure 5. Projected percentage of productive area (> 50 m^3/ha and 70 dm^3/stem) for black spruce for four levels of change: no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5) in growth/fire activity, and without fires.

Without considering fires, for black spruce, most of the districts (53%) would encompass more than 50% of productive area, except for a small area in the north and in the west (Figure 5 top left panel). When considering the current fire regime, most districts in the northernmost part of the study area (63%) are mostly unproductive while these proportions drop to 37% in the south (Figure 5 top right panel).

As the level of change in the fire regime increases with climate change, areas with a low percentage of productive area increase and expand southward (Figure 5 third column panels). On the contrary, as the level of change in growth increases, areas with a low percentage of productive area decrease and move northward (Figure 5 first and second column panels). Currently (no change in growth and in fire regime), 69% of the districts ≥ 20% of productive area, 37% ≥ 50%, 2% ≥ 80%. With high changes in growth and fire regime, 59% of the districts ≥ 20% of productive area, 20% ≥ 50%, 1% ≥ 80%.

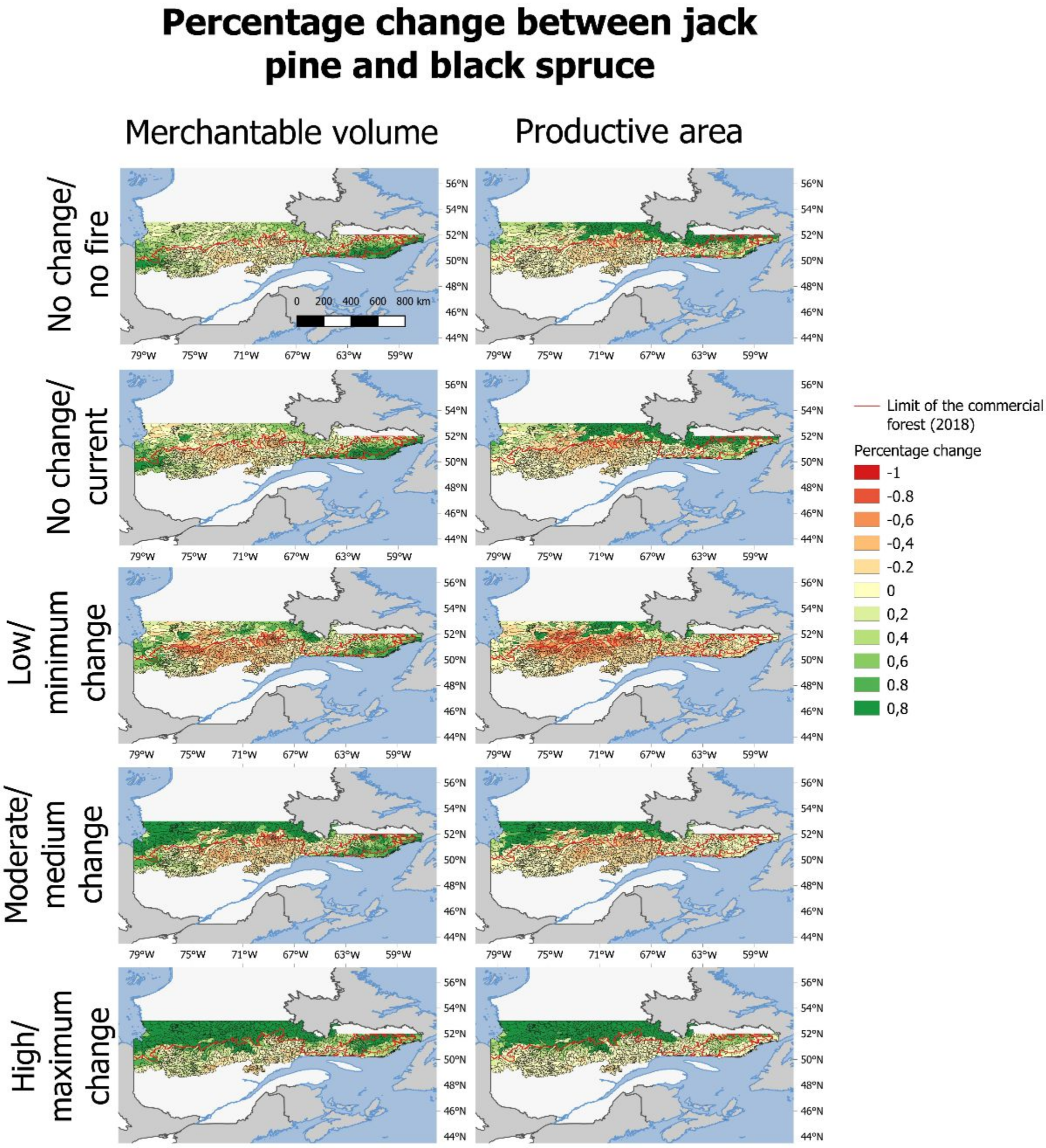

Figure 6. Projected change of merchantable volume and productive area (50 m3/ha and 70 dm3/stem) between black spruce and jack pine for five levels of change (growth/fire activity): no change/no fire, no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5).

Compared with black spruce, with current fire activity and no growth change (present), jack pine merchantable (Figure 6 left panels) volume is better than black spruce in the southwest, north-central and east, but worse in the south-central and northwest. With minimum fire activity and low growth change (2011-2040 ESM2–RCP 8.5), a significant decrease in jack pine merchantable volume compared to black spruce can be observed in the central and southern regions. A better jack pine merchantable volume is still observed in the east, west and north central regions. With medium fire activity and moderate growth change (2071-2100 ESM2–RCP 4.5), jack pine merchantable volume is better than black spruce again in the north and east, but worse in the south-central. With maximum fire activity and high growth change (2071-2100 ESM2–RCP 8.5), jack pine merchantable volume is better than black spruce across the northern half of the study area. A worse jack pine merchantable volume can be observed only in a few south-central districts.

For the productive area (Figure 6 right panels), there is a northern region where jack pine has a much better productive area than black spruce. This area is the smallest with minimum fire activity and low growth change but widens and moves southward as the level of growth changes and fire activity increases until it covers the entire northern half of our study area. A central region with a lower jack pine productive area than black spruce can also be found in our study area. This area is the largest with minimum fire activity and low growth change but decreases as the level of growth changes and fire activity increases until it almost disappears.

DISCUSSION

Our main goal was to evaluate the cumulative impact of climate change on growth and on fire activity on Quebec's boreal forest timber supply. Our results show that as temperature increases, growth increases, resulting in an increase in total volume. In parallel, fire activity also increases with warming, thereby contributing to reducing total volume. Synergically, as fire activity increases, the positive effect of warming on total volume is reduced: the effect of growth improvement on productivity will fade out as the burned area becomes more extended. Warmer conditions can lead to a longer vegetative season and thus promote growth of trees (Chmielewski and Rötzer 2001; D'Orangeville et al. 2016, 2018; Hember et al. 2017; Menzel and Fabian 1999; Messaoud and Chen 2011; Moreau et al. 2020; Price et al. 2013) but also leads to favorable conditions for fires, which results in increased fire activity (Balshi et al. 2009; Wotton et al. 2010; de Groot et al. 201.3; Boulanger et al. 2014; 2017; Wang et al. 2017).

Our results demonstrate the importance of taking fire into account when projecting future merchantable volume. Taking into account only the effect of a changing climate on tree growth leads to an overestimation of productive areas, resulting in an overestimation of the total volume and thus of the available timber supply for harvesting (Gauthier et al. 2015c; Cyr et al. 2022). Gauthier et al. (2015c) discussed the risk of not considering fire in our study area. Not only does our study support this result, but it also shows that it will be even more necessary to consider fire risk to merchantable volumes in the future under global warming.

Although the effect of fire suppression was not specifically considered, we believe that it would have had limited impact on our results. First, our current fire activity is calculated over a period of time when suppression resources were equivalent to those available today. Regarding fire suppression, our study area is separated into two parts. The southern part corresponds to the full response zone called intensive protection zone. In this area, the Forest Fire Protection Agency of Quebec (Société de protection des forêts contre le feu, SOPFEU) aims to systematically control all fires. The northern part of our study area corresponds to the Northern Protection Zone. Although all fires occurring in this zone are detected, only some of them are fought to ensure the protection of Quebec's communities and strategic infrastructures (SOPFEU, 2018). For the southern part of our study area, Cardil et al. (2019) showed that despite a good fire suppression system, fires in this area are more rarely controlled and result in large areas burned. As fires tend to occur simultaneously, they often create overflow situations (Gillett et al., 2004). During extreme weather conditions, these overflows are then responsible for large areas burned despite suppression efforts (Danneyrolles et al., 2021). With the prediction of increased fire activity due to climate change (Boulanger et al., 2014), more situations leading to large fires will occur, particularly in the boreal regions (Wotton et al., 2010). Hence the importance of including fires in all management phases to ensure sustainable forest management, especially under climate change.

One unforeseen outcome of the study is that, although the productive area would be greatly reduced with changes in the fire regime, there is an increase in the merchantable volume in the areas that remain productive. In the future, therefore, harvestable areas would decrease, but the productive areas should have a higher merchantable volume with larger stems and/or higher tree density. This unexpected result indicates that by not taking into account growth change due to climate change and only fire activity under climate change, we can also underestimate the merchantable volume, and accordingly the available timber supply in productive areas.

In terms of productive areas, our results show that the study area is divided in two, with a productive area in the south and an unproductive area in the north. As the level of change in fire regime increases, unproductive areas increase and move southward. As the level of change in growth increases, the merchantable volume of productive areas increases in the south. Even without fire and with improved growth, the south remains much more productive than the northern ones with areas in the south reaching up to 200 m^3/ha and the northern area not exceeding 90 m^3/ha. These results are in agreement with those of Gauthier et al. (2015c) who found this same contrast between the south and the north. This zone with low productivity, and particularly vulnerable to fire and climate change, stretches from west to east along the northern shore of Lake Mistassini and a portion of the east side of the Gulf of St. Lawrence. The boreal forest in the northern part of our study area is thus exposed to arid climatic conditions and grows on low productivity surface deposits (like organic plains of Abitibi and rock deposits of the North Shore) (Gauthier et al. 2015c).

Our results also suggest an advantage of jack pine over black spruce, especially in the northern half of our study area. Black spruce is a competitive species and tends to dominate on mesic sites, whereas jack pine is fast growing and can establish more easily on poor sites, especially following fire (Burns and Honkala 1990). In the southern areas where an increase in black spruce merchantable volume is observed, there would be limited gain in adding jack pine. However, in the northern half of our study area, characterized by low productivity and high vulnerability to fire and climate change, it might be interesting to consider jack pine over spruce in forest management, e.g. for plantations. Though, as this area is not easily accessible, potential gains in merchantable volume and productive area would depend on considerable financial investment that could be at risk notably when considering regeneration failure. Indeed, the northern half of our study area, characterized by low productivity and high vulnerability to increased fires due to climate change could also be particularly vulnerable to regeneration failure. Natural disturbances such as fire are the dominant cause of stand opening and thus of decreased productivity (Rapanoela et al. 2016; Splawinski et al. 2019; Cyr et al. 2022, Baltzer et al. 2021). However, the impact of loss of stem density produced by regeneration failure was also not considered in this study.

Our combination of different methods projecting tree growth, fire activity and stand productivity, is a valuable strategic method for evaluating how vulnerable a region may be to climate change. In addition, it allows the estimation of the potential timber supply in each district. This is helpful to guide current and future forest management at the northern limit of current commercial forestry. In the northern part of our study area, even without taking fire risk into account, it is quite unlikely that the forest could be managed sustainably and this becomes less and less probable in the future as suggested by our projections. Indeed, these districts already have a very low proportion of productive areas. In contrast, the southern portion of our study area has the potential to be sustainably managed. Not only is the productive area portion of this zone minimally affected by increased fire, but its merchantable volume will likely be also favorably affected by improved growth. This area in the south, easier to access, shows favorable conditions for a timber supply increase, and seems interesting for reforestation programs.

As we are mostly in a northern environment, it is possible that the growth model used (Pau et al. 2022), which is based on an observed temperature range of -2.7°C to 3.2°C, is not wide enough to include the 4^0C threshold at which warming becomes detrimental to growth, as observed by other studies (Pedlar and McKenney 2017). However, the combination of different levels of potential change in growth and fire allows us to forecast scenarios where fire or growth projections would be over or underestimated. Our study did not take into account the local adaptations of black spruce populations to climate. A recent study conducted on black spruce populations from different geographic provenances established in a common garden near Chibougamau provided indications that local black spruce populations were poorly adapted to the changing climate (Girardin et al. 2021b). This was demonstrated by lower productivity of local populations in comparison with populations originating from southern provenance locations. It is therefore likely that it would be possible to increase black spruce productivity by selecting more efficient and resilient provenances in the face of a changing climate. However, our productivity threshold (50 m^3/ha and 70 dm^3/stem) also remains a minimum threshold since the absolute harvestable age, which ensures maximum wood production per stand, is on average 21 years older in our study area than the minimum age for reaching the productivity threshold (Raulier et al., 2013). In a management context, aiming for harvest at absolute harvestable age would therefore increase vulnerability to fire even further as exposure time would be prolonged. SI could be overestimated due to the selection of dominant or co-dominant trees which could also lead to an underestimation of the vulnerability to fire since a smaller site index would also increase the exposure time. Finally, post-disturbance densification of hardwood species such as poplar or birch was also not considered and may contribute to reduced merchantable volume (Baltzer et al. 2021; Augustin et al. 2022).

CONCLUSION

Our study shows the importance of incorporating both fire and growth in strategic forest management planning (Savage et al. 2010; Leduc et al. 2015; Gauthier et al. 2015c). It is even more important when considering the extreme impacts of climate change. Not integrating fires leads to an overestimation of the productive area, creating a sharp contrast between timber volume projections and real volumes that incorporate fire activity under climate change, that can lead to a decline of the Quebec boreal forest (Paradis et al. 2013; Gauthier et al. 2015c; Cyr et al. 2022). In light of our results, the forest area that can be sustainably managed is thus likely to decrease with climate change. As unproductive areas increase and move southward with projected changes, it is very unlikely that sustainable forest management could be extended northward of the current commercial forestry limit in the future. However, opportunities in relation to increased productivity in some areas south of the northern limit would benefit to be explored. Finally, future work should be devoted to evaluate the impact of regeneration failures on our results.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study is the property of the Ministry of Forests, Wildlife and Parks of Québec. The data are available upon request.

AUTHOR INFORMATION

Author contributions

SG and Y. Bergeron supervised the project. HO provided the data from the Ministry of Forests, Wildlife and Parks of Québec. MP projected the change in tree growth due to climate change and Y. Boulanger projected the future fire activity. HO provided the script for the exposure time and the non-parametric k-NN matching method. MP conducted data analysis and synthesis. MP and SG interpreted the results. MP drafted the manuscript. All the authors reviewed and contributed actionable feedback that improved the manuscript.

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Competing interests

The authors declare there are no competing interests.

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Table 1. Exposure time or minimum age at which a stand of given site index (SI, height in m at 50 years) and relative density index at 100 years (RDI100) exceeds the two-parameter productivity threshold (50 m^3/ha and 70 dm^3/stem).

		SI											
		Black spruce						Jack pine					
		12	14	16	18	20	22	12	14	16	18	20	22
RDI100	0.1	130	110	100	95	90	90	110	90	80	75	70	70
	0.3	100	85	75	70	65	65	85	70	65	60	55	55
	0.5	90	60	50	50	45	45	130	55	45	45	40	40
	0.7	160	55	40	30	25	25	140	65	40	30	25	25
	0.9	185	70	50	40	35	30	140	95	55	40	35	30

Table 2. Level of growth and fire change, their corresponding Period/RCP and their corresponding increase in mean temperature as averaged over the whole study area.

Period/RCP	Present	2011-2040 ESM2–RCP 8.5	2071-2100 ESM2–RCP 4.5	2071-2100 ESM2–RCP 8.5
Increase in mean temperature	T= 0^{0}C	+1.3^{0}C	+3.4^{0}C	+6.6^{0}C
Black spruce growth change	**No change** SI = 12.82m	**Low** +10.5%	**Moderate** +27.3%	**High** +59.7%
Jack pine growth change	**No change** SI= 13.38m	**Low** +4%	**Moderate** +17%	**High** +82.1%
Fire activity	**Current** Burn rates = 0.79% y^{-1}	**Minimum** +84%	**Medium** +326%	**Maximum** +620%

Table 3. Climate scenarios for black spruce (BS) and jack pine (JP).

		Growth Change			
		No change	Low	Moderate	Hight
Fire activity	Without fire	BS JP	BS	BS	BS
	Current	BS JP	BS	BS	BS
	Minimum	BS	BS JP	BS	BS
	Medium	BS	BS	BS JP	BS
	Maximum	BS	BS	BS	BS JP

Table 4. Results from the two-way ANOVA on the influence of level of change in growth and burn rate on mean merchantable volume (m^3/ha).

Climate-induced effect	Sum of squares	Mean of squares	DF	F value	p value
Growth change	2351522	783841	3	6603.098	<.0001
Fire activity	2523996	841332	3	7087.407	<.0001
Growth change x Fire activity	33187	3687	9	31.063	<.0001

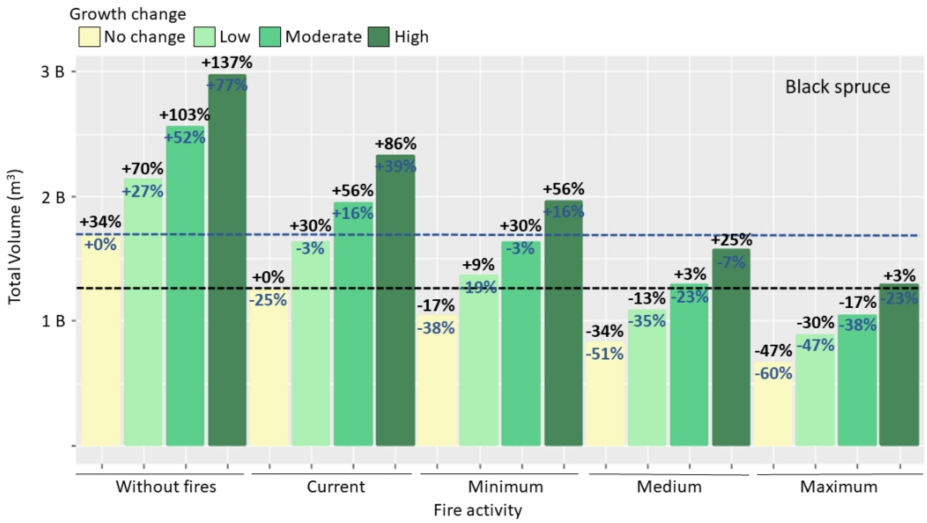

Figure 1. Projected total volume (m^3) for black spruce for four levels of change (growth/fire activity): no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5) and without fires. Percentages in blue report the changes in volume compared to no change in growth without considering fires (dotted blue line) and in black, percentage change in volume compared to no change in growth and no change in fire (dotted black line).

855x481mm (38 x 38 DPI)

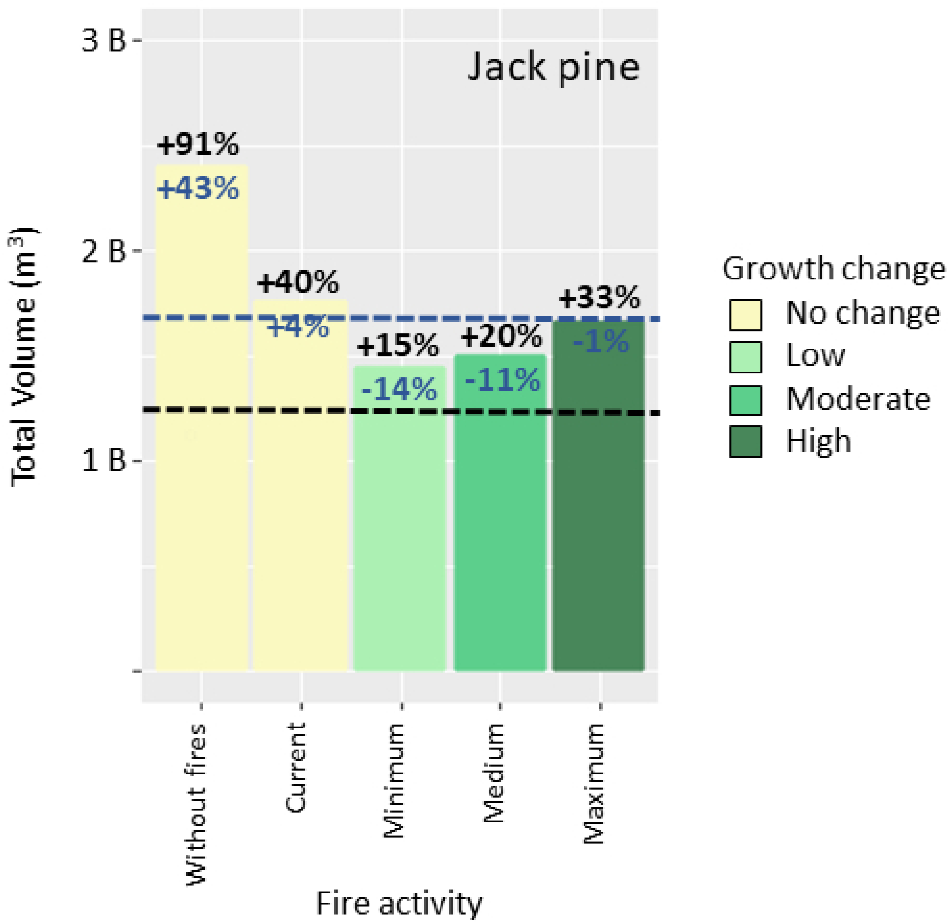

Figure 2. Projected total volume (m^3) for jack pine for four levels of change (growth/fire activity): no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5) and without fires. Percentages in blue report the changes in volume compared to no change in growth without considering fires for black spruce (dotted blue line) and in black, percentage change in volume compared to no change in growth and current fire for black spruce (dotted black line).

348x340mm (38 x 38 DPI)

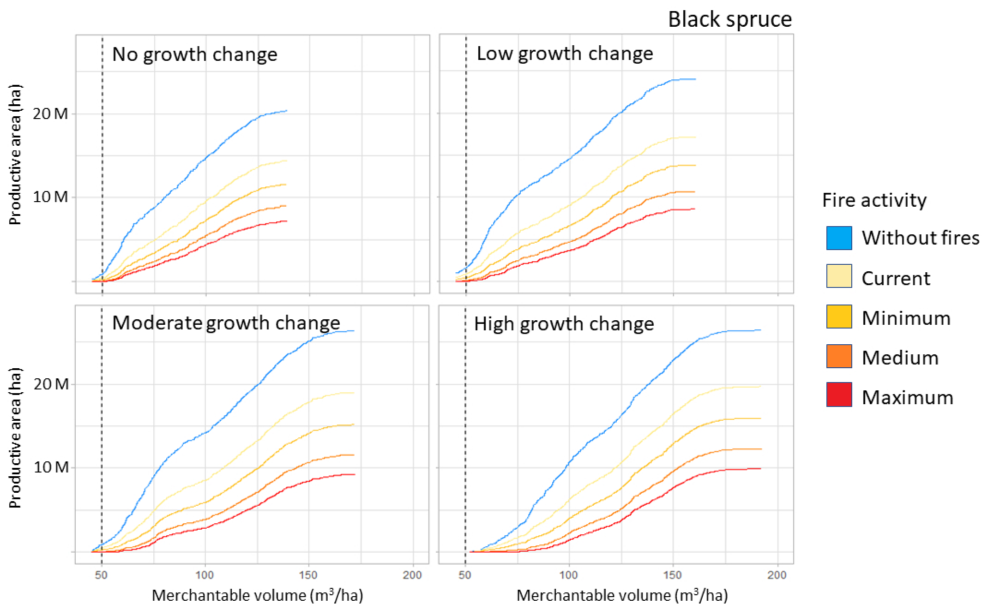

Figure 3. Projected cumulated productive area (ha) according to merchantable volume (m^3/ha) for black spruce for four levels of change (growth/fire activity): no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5) and without fires.

723x446mm (38 x 38 DPI)

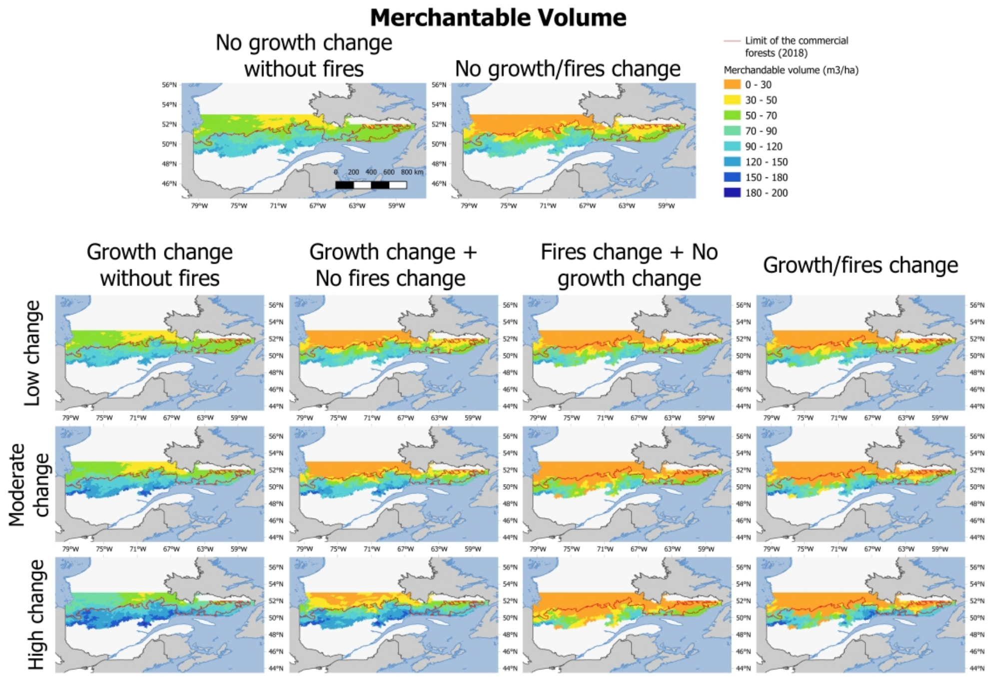

Figure 4. Projected merchantable volume (m^3/ha) (relative to the area without fire at each level of growth change) for black spruce for four levels of change: no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5) in growth/fire activity, and without fires.

1070x756mm (157 x 157 DPI)

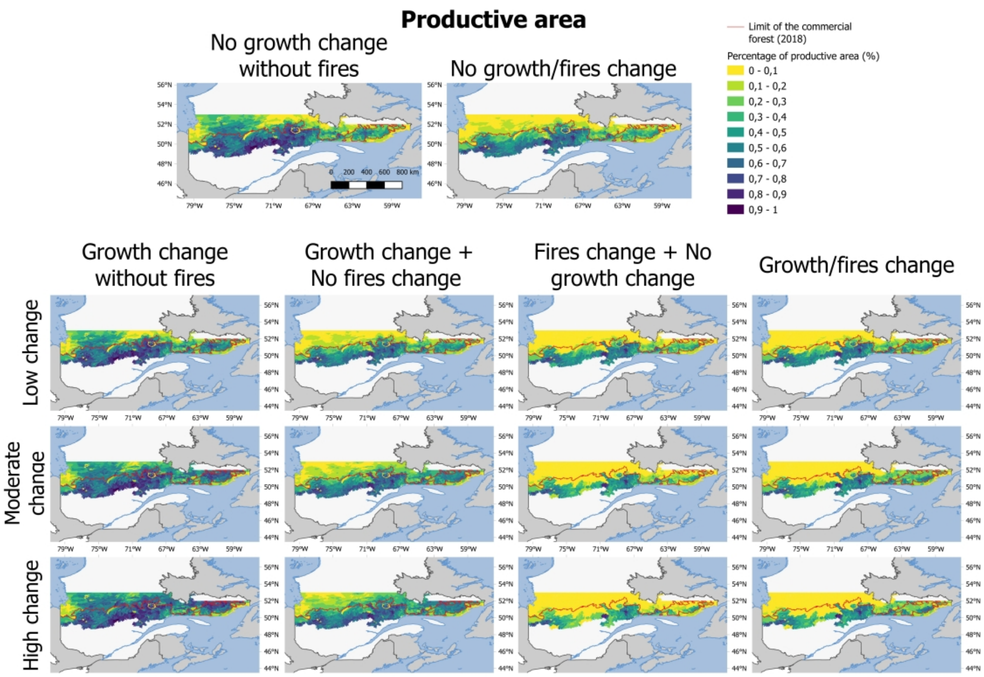

Figure 5. Projected percentage of productive area (> 50 m^3/ha and 70 dm^3/stem) for black spruce for four levels of change: no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5) in growth/fire activity, and without fires.

1070x756mm (157 x 157 DPI)

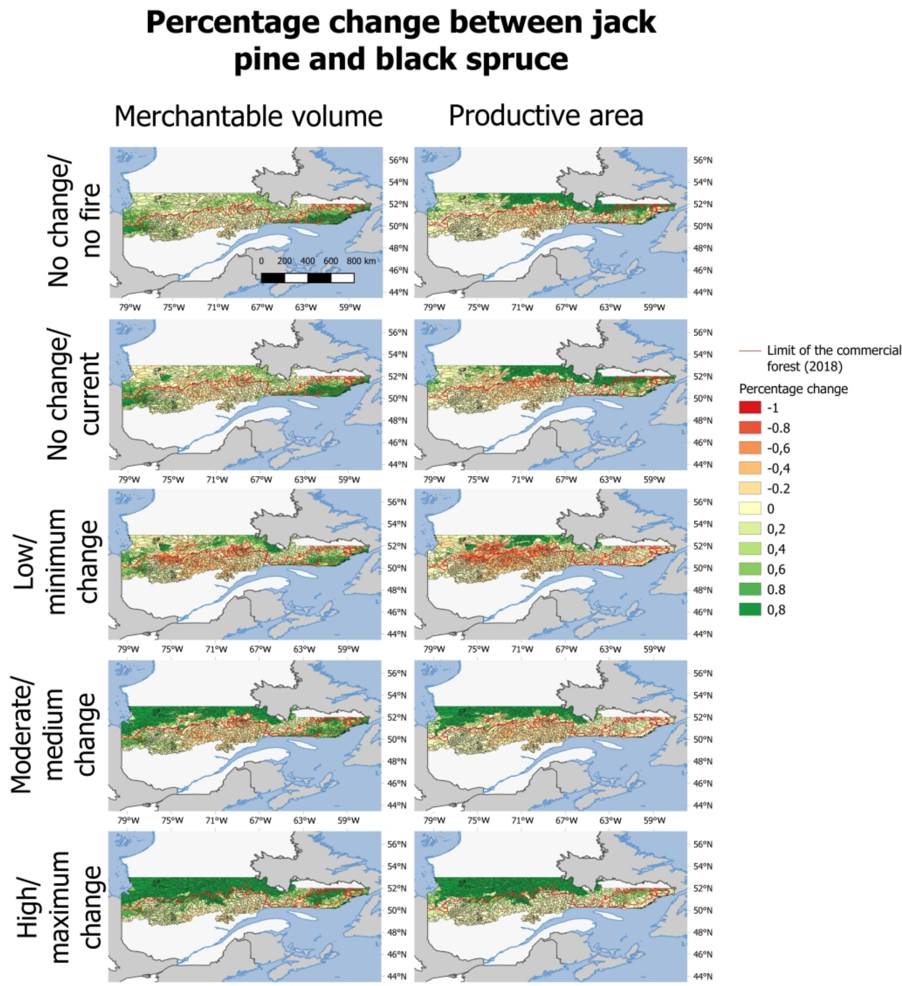

Figure 6. Projected change of merchantable volume and productive area (50 m^3/ha and 70 dm^3/stem) between black spruce and jack pine for five levels of change (growth/fire activity): no change/no fire, no change/current (present), low/minimum (2011-2040 ESM2–RCP 8.5), moderate/medium (2071-2100 ESM2–RCP 4.5) and high/maximum (2071-2100 ESM2–RCP 8.5).

820x856mm (157 x 157 DPI)