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Mitigating post-fire regeneration failure in boreal landscapes with reforestation and variable retention harvesting: At what cost?

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Abstract: Successive disturbances such as fire can affect post-disturbance regeneration density, with documented adverse effects on subsequent stand productivity. We conducted a simulation study to assess the potential of reactive (reforestation) and proactive (variable retention harvesting) post-fire regeneration failure mitigation strategies in a 1.37 Mha fire-prone boreal landscape dominated by black spruce (*Picea mariana* (Mill.) B.S.P.) and jack pine (*Pinus banksiana* Lamb.). We quantified their respective capacity to maintain landscape productivity and post-fire resilience, as well as their associated financial returns under current and projected (RCP 8.5) fire regimes. While post-fire reforestation with jack pine revealed to be the most effective strategy to maintain potential production, associated costs quickly became prohibitive when applied over extensive areas. Proactive strategies such as an extensive use of variable retention harvesting, combined with replanting of fire-adapted jack pine only in easily accessible areas, appeared as a more promising approach. Despite this, our results suggest an inevitable erosion of forest productivity due to post-fire regeneration failure events, highlighting the importance of integrating fire a priori in strategic forest management planning as well as its effects on long-term regeneration dynamics.

Key words: post-fire regeneration failure, reforestation, variable retention harvesting, post-fire resilience, black spruce, jack pine.

Résumé : Les perturbations successives, telles que les feux, peuvent influencer la densité de la régénération observée après une perturbation et avoir un effet indésirable connu sur la productivité des futurs peuplements. Nous avons mené une étude de simulation pour évaluer le potentiel de stratégies réactives (reboisement) et proactives (coupe à rétention variable) d'atténuation des échecs de la régénération après un feu dans un paysage boréal d'une superficie de 1,37 Mha, sujet aux feux et dominé par l'épinette noire (*Picea mariana* (Mill.) B.S.P.) et le pin gris (*Pinus banksiana* Lamb.). Nous avons quantifié leur capacité respective à maintenir la productivité et la résilience après un feu à l'échelle du paysage, de même que leurs rendements financiers sous les régimes de feu actuels et projetés (RCP 8.5). Bien qu'un reboisement de pin gris après un feu se soit avéré la stratégie la plus efficace pour maintenir la production potentielle, les coûts associés à cette stratégie sont rapidement devenus prohibitifs lorsqu'elle était appliquée sur de vastes superficies. Une approche plus prometteuse consiste en une stratégie proactive telle qu'une application à grande échelle de la récolte à rétention variable combinée au reboisement uniquement dans les zones facilement accessibles d'une espèce bien adaptée au passage du feu comme le pin gris. Malgré tout, nos résultats indiquent qu'une diminution de la productivité forestière est inévitable en raison d'épisodes d'échec de la régénération après un feu. Ce constat souligne l'importance d'intégrer a priori le feu dans la planification stratégique de l'aménagement forestier de même que ses effets sur la dynamique de la régénération à long terme. [Traduit par la Rédaction]

Mots-clés : échec de la régénération après un feu, reboisement, récolte à rétention variable, résilience après un feu, épinette noire, pin gris.

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Introduction

Inclusion of fire risk into all phases of planning is increasingly being recognized as a necessity to ensure sustainable forest management (Savage et al. 2010). It becomes particularly relevant in the development of adaptive and mitigative strategies responding to changes in disturbance regime driven by climate change (Raulier et al. 2013; Gauthier et al. 2015a, 2015b; Splawinski et al. 2019b). Reactive management approaches have typically been favored due to the uncertainty of fire occurrence over space and time; however, it has often been suggested that sustainable forest management strategies will require proactive approaches to fire risk (Savage et al. 2013; Raulier et al. 2013; Leduc et al. 2015).

Disturbance regimes in the boreal forest of eastern Canada are characterized by large stand-replacing wildfires (Bergeron et al. 2001, 2004; Stocks et al. 2002) that shape forest community structure, composition, and patterns of succession (Payette 1992). Although the dominant tree species, black spruce (*Picea mariana* (Mill.) B.S.P.) and jack pine (*Pinus banksiana* Lamb.), are well-adapted to fire and typically follow a self-replacement dynamic over time (Rudolph and Laidly 1990; Viereck and Johnson 1990), their resilience is limited by the frequency (Brown and Johnstone 2012; Baltzer et al. 2021) and severity (Pinno et al. 2013; Splawinski et al. 2019c) of fire events, which are expected to increase over the next century (Flannigan et al. 2013; Boulanger et al. 2014). Regions that are already characterized by a relatively short fire cycle and low productivity would be most vulnerable to further changes in burn rate and (or) forest management practices (i.e., harvest rate), and could require significant and intensive treatments to maintain both forest and stand productivity under progressively shorter fire cycles (Splawinski et al. 2019b; Whitman et al. 2019; Schab et al. 2021).

Post-disturbance reforestation can help to avoid such loss of productivity (Thiffault and Jobidon 2006; Thiffault et al. 2013) and increase carbon sequestration capacity (Fargione et al. 2018; Domke et al. 2020; Drever et al. 2021). However, it can be costly due to scarification and planting, particularly when road access is needed (James et al. 2007; Splawinski et al. 2019a). In recent decades, variable retention and partial harvesting have been increasingly considered as alternatives to clearcutting as a means of maintaining forest structure, habitat, and biodiversity (Franklin et al. 1997; Montoro Girona et al. 2018; Moussaoui et al. 2020; Kim et al. 2021). The retention of cone bearing seed trees during harvest can ensure that a sufficient aerial seed bank is present to regenerate a stand adequately should it burn before the post-harvest new cohort reaches reproductive maturity, thereby increasing stand resilience to fire and avoiding the need for reforestation. It does not require the additional maintenance cost of road access, but requires the retention of volume (and associated loss of revenues) that would otherwise have been harvested (Splawinski et al. 2019a).

The total cost of silvicultural treatments required to maintain productivity is influenced not only by the area affected by regeneration failure (the shorter the fire cycle and the younger the forest, the more extensive the area) but also by on-site accessibility. Road construction represents one of the most important investments to harvest available wood volume and to carry out further silviculture efforts. Road costs are mandatory when developing management strategies for coherence between existing or future access and management objectives from a financial point of view (Acuna et al. 2010). Conversely, the long-term financial impact of avoiding intervention altogether represents a potentially significant loss in productive areas and associated timber volume over time (Acuna et al. 2010; Splawinski et al. 2019a, 2019b). Finally, the prevailing disturbance regime and any anticipated changes must be carefully considered when selecting silvicultural practices to include as part of a long-term adaptive management strategy, since the potential of losing investments to fire is more probable under shorter fire cycles (Raulier et al. 2013; Rodriguez-Baca et al. 2016; Rijal et al. 2018).

Through the use of a simulation model, our main objective was to assess the potential impact of regeneration failure on the productivity of a forest management unit (FMU) over a planning horizon of 150 years. We also aimed to compare the outcome of proposed post-fire regeneration failure mitigation strategies (variable retention harvesting and reforestation) on the maintenance of forest productivity and post-fire resilience, while considering financial returns. To achieve this, we first developed and implemented a regeneration module derived from the work of Splawinski et al. (2014) and integrated it into a previously published model (Cyr et al. 2016; Splawinski et al. 2019b) allowing a more nuanced evaluation of changes in stand and FMU's productivity. Using this simulation approach, we then assessed the potential impacts of changes in regeneration density on both productive area and mean stand productivity within the FMU over the planning horizon. Simulations were conducted with the observed harvest rate of the FMU and under current and projected annual area burned.

Methodology

Study area and initial conditions

The study area is located in the boreal forest of northwestern Quebec, Canada, within the western black spruce – feather moss bioclimatic sub-domain (Saucier et al. 2011; Fig. 1), and is characterized by a moderate to high burn rate (Gauthier et al. 2015a). It covers a total area of 1.37 Mha located on publicly own lands, south of the northern limit of commercial forests in this province (Jobidon et al. 2015) and west of Lake Mistassini. The study area is dominated by pure black spruce and jack pine stands found predominantly on till, organic, fluvioglacial, and glacio-lacustrine surficial deposits, with large bodies of water covering 10.6% of the area. This region has a sub-polar continental climate, with a growing season of four to five months, an average annual temperature ranging from −2.5 to 0 °C, and average annual precipitation of 700 to 1100 mm (Fick and Hijmans 2017). Industrial harvesting began in the 1970s in this region, with clearcutting, which was replaced with careful logging around advance growth (CLAAG) in the late 1980s. Both are variations of the clearcut system, no distinctions will henceforward be made between them.

Forest inventory maps generated under the 4th decennial governmental inventory updated to 2015 (Ministère des Forêts, de la Faune et des Parcs 2015) were used to initialize stand simulations. Stand-level data was used to group tree species into three compositional classes based on dominant species or species group (black spruce, jack pine, or deciduous) and to determine the initial stand age at the onset of simulations (Splawinski et al. 2019b). Productive forests, defined as stands producing at least 30 m³/ha of merchantable wood at 120 years of age, made up 71.8% (0.878 Mha) of the total land area. Although stands belonging to the deciduous class were included in the areas submitted to the fire regime in our simulations, they represent a small portion of the landscape as jack pine and black spruce make up the vast majority (96.5%) of productive land, i.e., 0.847 Mha. They were not harvested and not examined in terms of regeneration failure as the species usually regenerate following fire, irrespective of frequency (Johnstone and Chapin 2006; Bergeron and Fenton 2012; Boucher et al. 2020). The actively managed forest was made of productive forest land with species of commercial interest (black spruce and jack pine) minus conservation areas, for a total of 640 350 ha, accounting for 46.8% of the total study area.

General modeling approach

Using the R software package (version 3.4.4; R Core Team 2020), we developed a spatially explicit model that simulated each year, stand aging and growth and up to four types of events. When happening, these events follow the order: fire, salvage logging, harvesting and post-fire planting. To ease computation, grid cell

Fig. 1. Location of study area within bioclimatic subdomain 6-West (western black spruce – feather moss bioclimatic sub-domain) of the boreal forest of northwestern Quebec, Canada. Base map and additional data from Ministère des forêts de la Faune et des Parcs (2021).
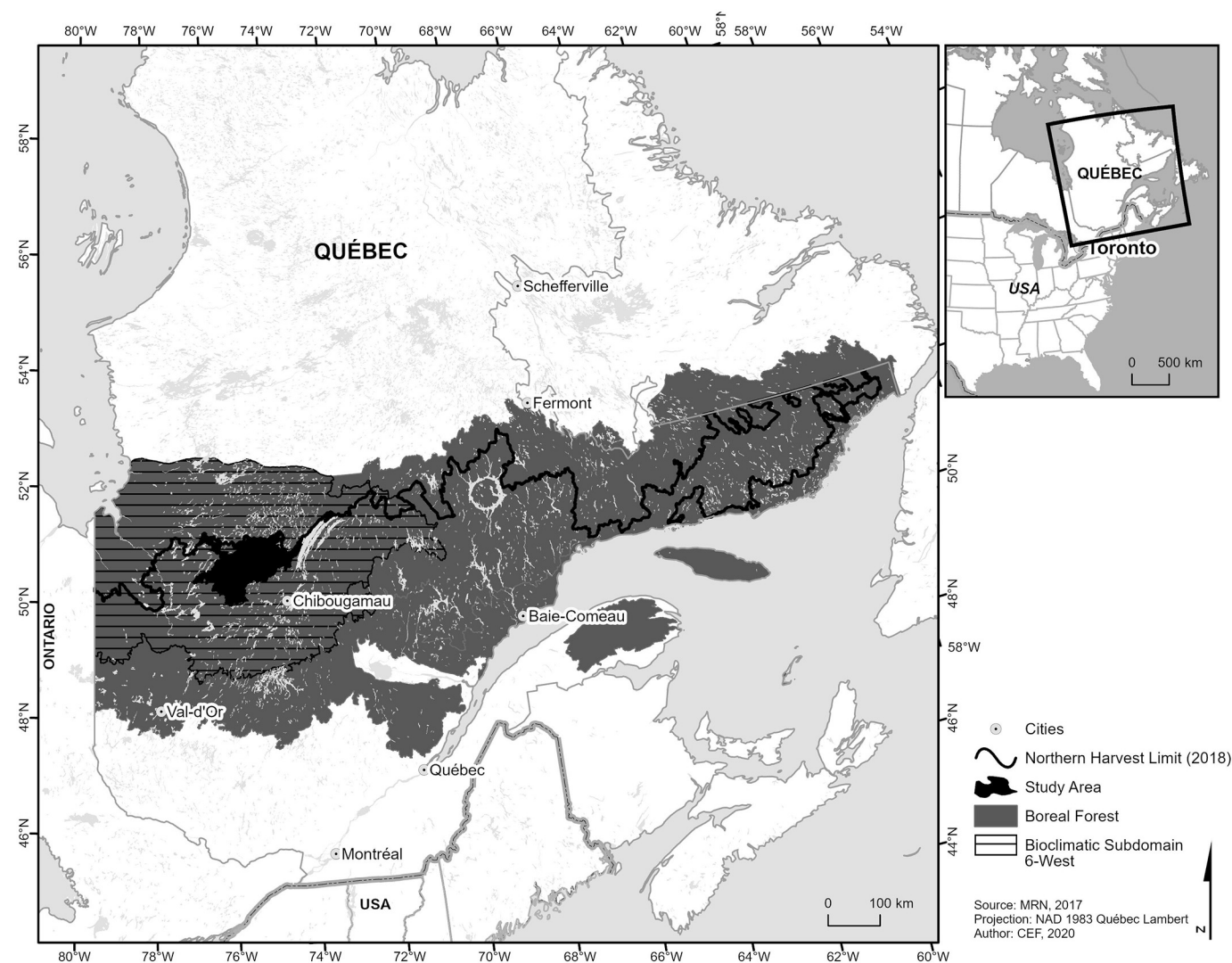
resolution was set at 500 m (25 ha). Stand attributes from the inventory polygon found at the center of each cell made up the simulated landscape grid. Additional details about the simulation study as well as the complete code to reproduce it are available online (https://github.com/dcyr/risqueAccidentRegen).

Growth and yield

Site index and relative density (RDI_{100}) indices were assigned to each black spruce and jack pine stand using a k-nearest neighbors imputation approach similar to that used by Gauthier et al. (2015*b*), based on climate and edaphic variables (surficial deposit and drainage). Stands were simulated as mono-specific and even-aged using Pothier and Savard (1998) growth and yield equations to track stem density, mean quadratic diameter, basal area and merchantable volume over the simulation period. Whenever a stand happened to burn during the simulations period, pre-fire stand age and basal area were used to calculate seed availability and regeneration density based on the regeneration module described below (see section Simulating post-fire regeneration), which determined post-disturbance regeneration density and the resulting RDI_{100}. The initial site index attributed to each

stand remained constant for the duration of simulations; only RDI_{100} was updated when a fire occurred.

Simulating fire

We simulated both the recently observed (1972 to 2009) and projected annual area burned under RCP 8.5 (Gauthier et al. 2015*b*). Respectively, those correspond to a mean fire cycle of 101 years (burn rate of 0.99%/year; current burn rate) and a linearly increasing probability of burning, reaching an equivalent of a 24-year fire cycle in 2070 (plateaued at ∼4%/year), as predicted under RCP 8.5 (Boulanger et al. 2014). The historical fire regime that we simulated incorporated fires of all origins. Because projections are calculated using a coefficient that multiplies the historical burn rates, all sources of ignition are implicitly included as well.

Our simulated landscape was made up of a combination of flammable (productive and unproductive forest, i.e., 89.4% of the study area; 1.22 Mha) and inflammable (waterways and non-treed land covers, i.e., 10.6% of the study area; (0.15 Mha). For each year, an annual burn rate was first determined together with the number of fires that were randomly ignited in the simulated landscape and could propagate to a predefined fire size using a

cellular automaton (Cyr et al. 2016). The targeted annual burn rates (BR) were achieved using the following relationship:

$$BR = \frac{\overline{N} \times \overline{S}}{A}$$

where $\overline{N}$ is the average annual number of fire events, $\overline{S}$ is the mean fire size, and A is the total inflammable area. The number of fire events at every yearly time step was modeled as a Poisson-distributed random variable of mean equal to the average number of fires per year. The size of each fire event was drawn from a log-normal fit of the empirical fire size distribution as documented by Gauthier et al. (2015b). If a fire event could not reach its targeted size, an additional cell was ignited with the remaining area as a new target size. More details on this approach can be found in Cyr et al. (2016) and Splawinski et al. (2019b). When a stand burned, its age was reset to 0 and its RDI_{100} was updated to reflect the new seedling density predicted by the post-fire regeneration module described below.

Simulating salvage logging

Immediately after fire, salvage logging opportunities were evaluated by comparing pre-fire stand attributes predicted using Pothier and Savard (1998) equations against eligibility thresholds currently used in the study area. An eligible stand had to have a standing volume ≥ 70 m³/ha, a more restrictive condition than the 50 m³/ha required in unburned stands, to account for fire-related volume losses (Splawinski et al. 2019a). A maximum of 70% of the eligible salvaging areas were then harvested, corresponding to the maximum salvage rate currently permitted to maintain a proportion of habitat representative of mature forest burns (Nappi et al. 2011). If the annual harvest rate target was not reached after salvage logging, the remaining area was harvested in unburned stands. The post-salvaged RDI_{100} was updated to reflect the new seedling density predicted by the post-fire regeneration module described below.

Simulating harvest

In management scenarios that included harvesting, an area-based harvest rate of 0.62%/year of the productive coniferous area under management was used, which is equivalent to the volume-based harvest rate currently allocated in this area (Bureau du forestier en chef 2014; Pelletier 2016). Stands eligible for harvesting were randomly selected among stands that were at least 76 or 90 years old, the average commercial maturity thresholds for jack pine and black spruce in that area, respectively, and that had a standing volume equal or greater than 50 m³/ha (commercial eligibility threshold). It was assumed that post-harvest regeneration maintained pre-harvest stand productivity, as this is a regulatory requirement in Quebec to assure adequate stocking. Stands that were previously harvested could be harvested more than once in the course of the simulation if they could reach age and volume eligibility criteria again.

Either clearcutting or retention harvesting was simulated. Variable retention harvesting was simulated as an alternative to clearcutting to assure that a persisting aerial seed bank produced a post-fire regeneration density yielding ≥ 30 m³ per hectare at 120 years (the threshold value between productive and unproductive forests in Quebec) should the stand subsequently burn. The area harvested was not adjusted for the volume retained, i.e., that total harvested volumes were systematically lower. The retained proportion of the stand was not considered part of the growing stand afterward. It was used as a 'floor' value for the regeneration module in the event of a subsequent fire, up until the cohort established just after the fire reached an equal basal area, at which point it continued to develop following Pothier and Savard (1998) equations.

Simulating post-fire regeneration

Contrary to post-harvest regeneration, the natural post-fire regeneration density was explicitly modeled to account for the documented effects of pre-fire stand attributes and inherent site productivity. Post-fire seedling density was predicted using empirically-based relationships documented in Splawinski et al. (2014) with minor modifications (see supplementary material 1[1]). More specifically, those relationships define the initial seed availability, the abscission schedule of seeds over the 6-year post-fire recruitment period, and seed/seedling survival based on seed mass, seedbed proportion, and granivory (Splawinski et al. 2014). Post-fire seedling density was also a function of age, using documented relationships between stand age and the proportion of cone-bearing trees for black spruce (Viglas et al. 2013) and jack pine (Briand et al. 2015) as multipliers (see supplementary material 1[1]).

We then applied a transfer function to translate seedling density predictions into an updated RDI_{100} that, in turn, directly influenced post-fire potential productivity. That transfer function is based on a quantile mapping approach (Maraun 2016), which is a statistical transformation that allows to rescale modeled values (e.g., seedling density) based on a distribution of corresponding observations (i.e., RDI_{100}). We assumed that the distribution of RDI_{100} values on the FMU is directly linked with the distribution of the post-fire number of seedlings that these same stands would have produced. We then used the empirical cumulative distribution of RDI_{100} from the ~1990 forest inventory as the observation dataset to fit a quantile mapping model using the 'qmap' R package (Gudmundsson 2016) to match the cumulative distribution of seedling density values predicted for the same dataset.

In cases where burned stands were salvaged logged, predicted seedling densities were adjusted prior to estimating RDI_{100} to account for the shortened abscission period, which was reduced from 6 years to 6 months to reflect the average fire-to-salvage time interval (Splawinski et al. 2014) and the removal of the remaining aerial seed-bank along with salvaged timber: 40% for black spruce and 81% for jack pine (Greene et al. 2013). A seedling mortality rate of 30% was thus applied, reflecting mortality induced by the passage of machinery along skid trails (Greene et al. 2006).

Simulating post-fire reforestation

Reforestation of post-fire and post-salvaged stands was simulated when predicted post-fire seedling density was below 2000 seedlings/ha. Planted stands had 2000 seedlings added to the natural regeneration density calculated in the regeneration module, implicitly reflecting the MFFP base stocking target of 60% (Marie-Ève Larouche, MFFP, personal communication).

Scenarios

A total of 15 scenarios were simulated, 9 under the current burned rate and 6 under future burned rates based on RCP 8.5 (Table 1). A more comprehensive set of scenarios were investigated under current burn rates to assess the relative efficiency of each post-fire regeneration failure mitigation option, while only the most extreme combinations of silvicultural treatments were investigated under future burn rates, assuming that the relative effectiveness of each treatment would remain comparable regardless of the burn rate. First, a scenario with fire only (no harvesting; S01) was developed to assess the impact of fire on regeneration failure and to compare with the other scenarios. A business-as-usual scenario (S02) combined fire, salvage logging and clearcutting as currently practiced in the FMU, allowing the assessment of the impact of harvesting and salvage logging on productivity loss. Seven scenarios of regeneration failure mitigation with various combinations of road access, reforestation or variable retention were developed under the current burn rate to assess their effects on landscape productivity and profitability (S03 to S09). Under future burn rates, in addition to no

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Table 1. Summary of simulated scenarios.

Scenario No.	Fire scenario (burn rate)	Type of harvesting (harvest rate)	Type of reforestation	Road access[a]	**Objectives** (Indicators)
S01	Current (0.99%/year)	No harvesting	Nil	N/A	**Effect of fire activity without forest management** (cumulative regeneration failure rate; estimated merchantable volume at 120 years of age; changes in forest productivity classes)
S02	Current (0.99%/year)	Clearcutting + post-fire salvage (0.62% productive coniferous forests)	Nil	N/A	**Business as Usual Current practices** (cumulative regeneration failure rate; estimated merchantable volume at 120 years of age; changes in forest productivity classes; financial returns)
S03	Current (0.99%/year)	Variable retention + post-fire salvage (0.62% productive coniferous forests with retention of basal area)	Nil	N/A	**Effect of switching from clearcutting to variable retention harvesting** (cumulative regeneration failure rate; estimated merchantable volume at 120 years of age; changes in forest productivity classes; financial returns)
S04	Current (0.99%/year)	Clearcutting + post-fire salvage (0.62% productive coniferous forests)	Pre-fire composition plantation	Existing	**Compare pre-fire composition vs jack pine plantation under existing road access** (cumulative regeneration failure rate; estimated merchantable volume at 120 years of age; changes in forest productivity classes; financial returns)
S05	Current (0.99%/year)	Clearcutting + post-fire salvage (0.62% productive coniferous forests)	Jack pine plantation	Existing	
S06	Current (0.99%/year)	Variable retention + post-fire salvage (0.62% productive coniferous forests with retention of basal area)	Pre-fire composition plantation	Existing	**With variable retention, compare pre-fire composition vs jack pine plantation under existing road access** (cumulative regeneration failure rate; estimated merchantable volume at 120 years of age; changes in forest productivity classes; financial returns)
S07	Current (0.99%/year)	Variable retention + post-fire salvage (0.62% productive coniferous forests with retention of basal area)	Jack pine plantation	Existing	
S08	Current (0.99%/year)	Clearcutting + post-fire salvage (0.62% productive coniferous forests)	Pre-fire composition plantation	Full	**Compare pre-fire composition vs jack pine plantation under full road access** (cumulative regeneration failure rate; estimated merchantable volume at 120 years of age; changes in forest productivity classes; financial returns)
S09	Current (0.99%/year)	Clearcutting + post-fire salvage (0.62% productive coniferous forests)	Jack pine plantation	Full	
S10	RCP 8.5 (from 0.99% to 4%/year)	No harvesting	Nil	N/A	**Effect of future fire activity without forest management** (cumulative regeneration failure rate; estimated merchantable volume at 120 years of age; changes in forest productivity classes)
S11	RCP 8.5 (from 0.99% to 4%/year)	Clearcutting + post-fire salvage (0.62% productive coniferous forests)	Nil	N/A	**Business as Usual under future fire activity: current harvesting rate** (cumulative regeneration failure rate; estimated merchantable volume at 120 years of age;

Table 1 (*concluded*).

Scenario No.	Fire scenario (burn rate)	Type of harvesting (harvest rate)	Type of reforestation	Road access[a]	Objectives (Indicators)
					changes in forest productivity classes; financial returns)
S12	RCP 8.5 (from 0.99% to 4%/year)	Variable retention + post-fire salvage (0.62% productive coniferous forests with retention of basal area)	Pre-fire composition plantation	Existing	**With variable retention, compare pre-fire composition vs jack pine plantation under existing road access** (cumulative regeneration failure rate; estimated merchantable volume at 120 years of age; changes in forest productivity classes; financial returns)
S13	RCP 8.5 (from 0.99% to 4% / year)	Variable retention + post-fire salvage (0.62% productive coniferous forests with retention of basal area)	Jack pine plantation	Existing	
S14	RCP 8.5 (from 0.99% to 4%/year)	Clearcutting + post-fire salvage (0.62% productive coniferous forests)	Pre-fire composition plantation	Full	**Compare pre-fire composition plantation vs jack pine plantation under future fire activity and full road access** (cumulative regeneration failure rate; estimated merchantable volume at 120 years of age; changes in forest productivity classes; financial returns)
S15	RCP 8.5 (from 0.99% to 4%/year)	Clearcutting + post-fire salvage (0.62% productive coniferous forests)	Jack pine plantation	Full	

[a]"Road access "existing" refers to everything located within a 2 km distance from the existing road network (55% of the study area). Road access "Full" refers to 100% of territory. N/A, not applicable.

harvesting (S10) and business-as-usual scenario (S11), we developed four more scenarios: scenarios S12 and S13 represent the most viable scenarios based on the first group of simulations, and S14 and S15 represent the best ones in terms of maintaining productivity but at a higher cost.

Two main regeneration failure mitigation strategies were tested: (1) a proactive strategy, in which variable retention harvesting is used as a means to ensure regeneration in the face of future fire, and (2) a reactive strategy, in which reforestation is used in burned areas affected by regeneration failure. For the latter, two plantation scenarios were examined, the first maintaining pre-fire composition (either black spruce or jack pine) and the second based exclusively on planting jack pine to take advantage of the earlier age of reproductive maturity of this species relative to black spruce (Viglas et al. 2013; Briand et al. 2015). The cost of plantation establishment, including site preparation (scarification and removal of residual stems) was set at CAN$1275/ha for black spruce, and CAN$1472/ha for jack pine (Splawinski et al. 2019*a*; Table 1).

To account for one important operational and financial constraint, we examined two road access scenarios. The first one reflects the current 2 km operational limit around the existing road network (Sonia Légaré, MFFP, personal communication), thus providing access to 55% of the study area, and the second scenario with presumed full (100%) access to the study area. No additional cost was associated with the existing access scenario. Conversely, the second road scenario with full access requires construction of winter roads that can withstand occasional access during the summer period for reforestation/stand management, representing an average expenditure of CAN$270/ha for sites located more than 2 km from the existing road network. Cumulative access costs for the FMU were tracked and capped to a maximum amount of CAN$74 800 530 (Splawinski et al. 2019*a*), corresponding to the development of a full-access road network. Maintenance and repair of the road network were not considered in the analysis.

Using a temporal horizon of 150 years, 100 simulations were produced under the 15 scenarios to account for the inherent stochasticity of forest fire occurrences. These scenarios were compared to assess the extent of regeneration failure and changes in forest productivity, the effect of adaptive silvicultural practices in mitigating productivity losses and the associated financial returns (Raulier et al. 2013, 2014). The following indicators were used to compare scenarios:

1. Cumulative regeneration failure (area %): The proportion of the initially productive area for which stands dropped below a potential production threshold of 30 m³/ha of merchantable volume at 120 years of age; which provided a means of monitoring the area that becomes unproductive over time. This threshold represents the minimal value for a stand to be included into the productive area in the FMU (Ministère des Forêts, de la Faune et des Parcs 2015). All stand productivity classes (next indicator) are based on the same 120-year time period.

2. Stand potential production (m³/ha@120): The average merchantable volume that any stands would produce should it reach 120 years. This indicator allowed us to assess the maintenance of potential productivity over time (Schab et al. 2021). Stand potential production was classified in 4 classes: unproductive, <30 m³/ha@120; low productivity, 30–50 m³/ha@120, commercially productive, 50–80 m³/ha@120; and highly productive >80m³/ha@120.

3. Cumulative harvested volume (m³): The cumulative harvested volume was monitored to derive associated revenues as well as opportunity cost of the variable retention strategy, and of the ability to maintain current wood flow over time.

Fig. 2. Evolution of areas affected by post-fire regeneration failure under the current (bold and dashed colored lines) and projected fire regimes (dotted black lines). Each line represents the median of 100 simulations (figure with untruncated *y*-axis in supplementary material 2 - Fig. S2.1[1]). [Color online.]
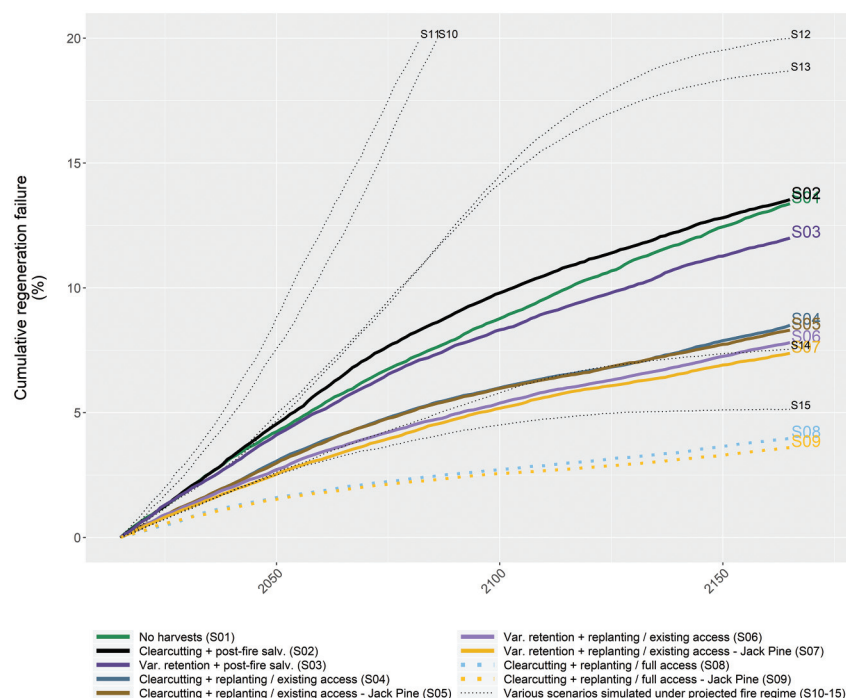
4. Financial returns: The royalties generated from the volume harvested by harvesting (corresponding to CAN\$13.75/m^3, based on documented average values in the study area; Bureau de mise en marché des bois 2018), minus the cost of plantation and road access, as an indicator to assess the profitability of each scenario.

5. Vulnerability of the landscape to regeneration failure: The proportion of initially productive stands (e.g., at time $T = 0$) that would become unproductive (<30 m^3/ha@120) in the event of a fire, as predicted using the post-fire regeneration module. Only jack pine and black spruce stands were considered, including those located in conservation areas, as well as those that could have previously dropped below the unproductive threshold.

6. Survival probability of plantation: The proportion of planted stands that did not burn before reaching the age of commercial maturity (76 years for jack pine and to 90 years for black spruce; Splawinski et al. 2019b). For that particular calculation, we only considered stands that were planted relatively early in the simulations and therefore could reach commercial maturity before the end of the 150-years simulations, i.e., at year 74 at latest for jack pine (150 – 76 = 74), and at year 60 at the latest for black spruce (150 – 90 = 60). All sites planted after those years were ignored.

Results

Regeneration failure and landscape productivity under current burn rate

Simulations showed a loss of landscape productivity due to post-fire regeneration failure over the course of the 150-years simulations in all scenarios to a variable extent. The cumulative loss of productive forest area ranged from 3.6% to 13.6% under the current fire regime (Fig. 2). Scenario S01 (without harvesting), S02 (business-as-usual), which involved clearcutting and no interventions in burned areas, and S03, with variable retention, were the most severely affected in terms of loss of productive forest area. The least affected scenarios

included post-fire reforestation; they were the most effective silvicultural treatment in terms of post-fire regeneration failure mitigation. Scenarios involving variable retention harvesting performed better than those without from the perspective of regeneration failure mitigation, but the effect of variable retention was not as strong as that of replanting. Salvage logging did not noticeably affect regeneration failure rates (scenarios not shown). The level of road access for replanting proportionally influenced the effectiveness of post-fire reforestation (S04 and S05 vs S08 and S09).

In terms of potential production, scenarios involving harvesting (clearcutting or variable retention) with not post-fire reforestation showed a steady decrease from 64.5 m^3/ha at the beginning of the simulations to just over 50 m^3/ha@120 at the end of the 150-year horizon (S02 and S03; Fig. 3). At the other end of the spectrum, the most effective combinations of treatments were those involving post-fire reforestation (S08 and S09) that showed a similar performance to S01 (no harvesting). The single most effective scenario (S09), which consisted in variable retention harvested combined with replanting all affected stands with jack pine without road access constraints, showed an 8.8% net decrease in average potential production at the end of the 150-years simulations. Therefore, it was not sufficient to entirely mitigate the erosion of average potential production, which dropped from 64.5 to 58.9 m^3/ha@120, just above the fire only scenario (S01). Again, scenarios involving variable retention (S06 and S07) showed intermediate results, while salvage logging had a negligible negative impact on average potential production (not shown).

Landscape productivity not only decreased because of a loss of productive forest areas, but it was also impacted by a net decrease in average potential production in stands that remained productive (Fig. 3; Table 2). In fact, although S01 appears to generate as many regeneration failures as S02 or S03 (Fig. 2), it performed much better with regard to the maintenance of highly productive areas (>80 m^3/ha@120; Table 2). After 150 years of harvesting, both scenarios without mitigation strategies (S02 and S03) only maintained about 50%–52% of the initial proportion in highly productive areas

Fig. 3. Evolution of mean potential production under the current (bold and dashed colored lines) and projected fire regimes (dotted black lines). Each line represents the median of 100 simulations while ribbons encompass 50% of simulations for selected treatments (figure with untruncated *y*-axis in supplementary material 2 - Fig. S2.2[1]). [Color online.]
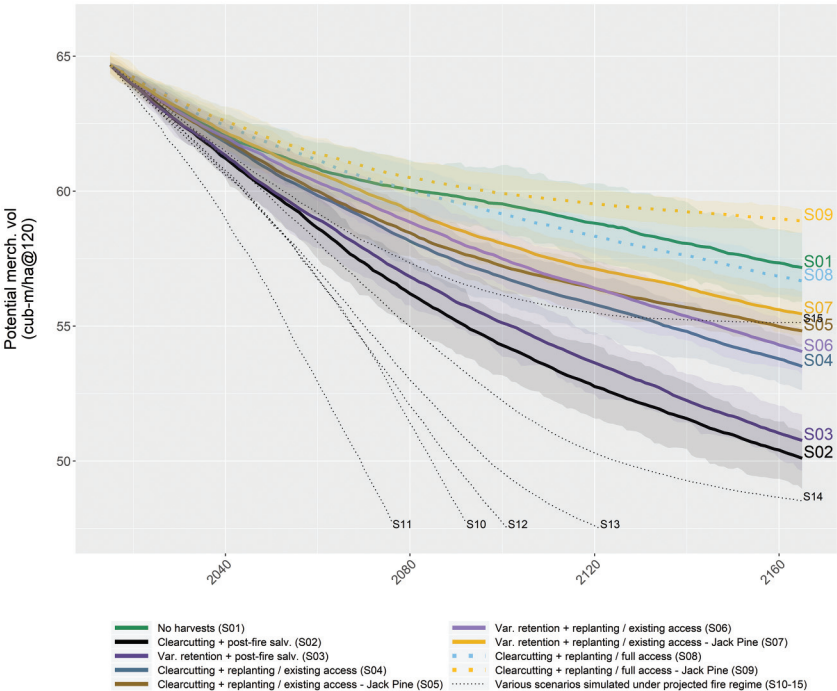

Table 2. Percentage of the area at 150 years and percentage of change between 0 and 150 years for each productivity class at the end of the simulation horizon, for all simulated regeneration failure mitigation scenarios.

Scenario No.	Proportion (%) of total forested area at 150 years (proportion (%) of initial conditions at 150 years)			
	Unproductive (<30 m³/ha at 120 years)	Low productivity (30–50 m³/ha at 120 years)	Commercially productive (50–80 m³/ha at 120 years)	Highly productive (≥80 m³/ha at 120 years)
S01	22.1 (253)	27.7 (109)	28.4 **(68)**	21.8 **(90)**
S02	22.3 (255)	35.0 (138)	30.5 **(73)**	12.2 **(50)**
S03	20.7 (237)	35.9 (142)	30.8 **(74)**	12.6 **(52)**
S04	17.2 (197)	31.0 (123)	39.1 **(94)**	12.7 **(52)**
S05	17.1 (194)	28.8 (110)	40.7 **(99)**	13.4 **(56)**
S06	16.6 (190)	31.1 (123)	39.2 **(94)**	13.2 **(54)**
S07	16.2 (184)	29.1 (111)	40.8 **(99)**	13.9 **(58)**
S08	12.7 (145)	27.0 (107)	47.0 (113)	13.4 **(55)**
S09	12.4 (141)	23.0 **(86)**	50.0 (123)	14.6 **(61)**
S10	42.4 (485)	44.9 (177)	9.8 **(24)**	2.9 **(12)**
S11	42.6 (487)	46.2 (183)	9.7 **(23)**	1.5 **(6)**
S12	28.7 (328)	41.5 (164)	27.3 **(66)**	2.5 **(10)**
S13	27.5 (312)	32.6 (125)	37.0 **(90)**	2.9 **(12)**
S14	16.3 (186)	37.1 (147)	43.7 (105)	2.8 **(12)**
S15	14.0 (158)	20.2 **(77)**	62.1 (151)	3.8 **(16)**

Note: Bold characters indicate a decrease in area. See Table 1 for the list of tested scenarios and their description. See supplementary Fig. S2.3[1] for an illustration of those values through the entire course of simulations.

(>80 m³/ha@120), much less than in the scenario with fire only (S01), which maintained 90% of the initial proportion. The proportion of highly productive areas decreased under all simulated scenarios, and only with the scenarios with full-access reforestation of jack pine (clearcutting or variable retention harvesting; S08 and S09) did the commercially productive class (50–80 m³/ha@120) actually increase (Table 2).

We also compared scenarios from the perspective of their respective average landscape vulnerability to fire, which we

defined as the proportion of the productive forest that would shift to a non-productive state in the event of a fire that would burn the entire simulated area (Fig. 4). In the fire-only scenario (S01), the vulnerability of the landscape slightly increased over time (16% to nearly 20% over 150-year runs). Scenarios based on clearcutting without (S02) plantation, or with plantation limited by road access (S04) resulted in a slight vulnerability increase as compared to S01.

From that perspective, post-fire reforestation did not substantially affect landscape vulnerability, except when all planted

Fig. 4. Future landscape vulnerability to post-fire regeneration failure under the current (bold and dashed colored lines) and projected fire regimes (dotted black lines). Each line represents the median of 100 simulations (figure with untruncated *y*-axis in supplementary material 2 - Fig. S2.4[1]). [Color online.]
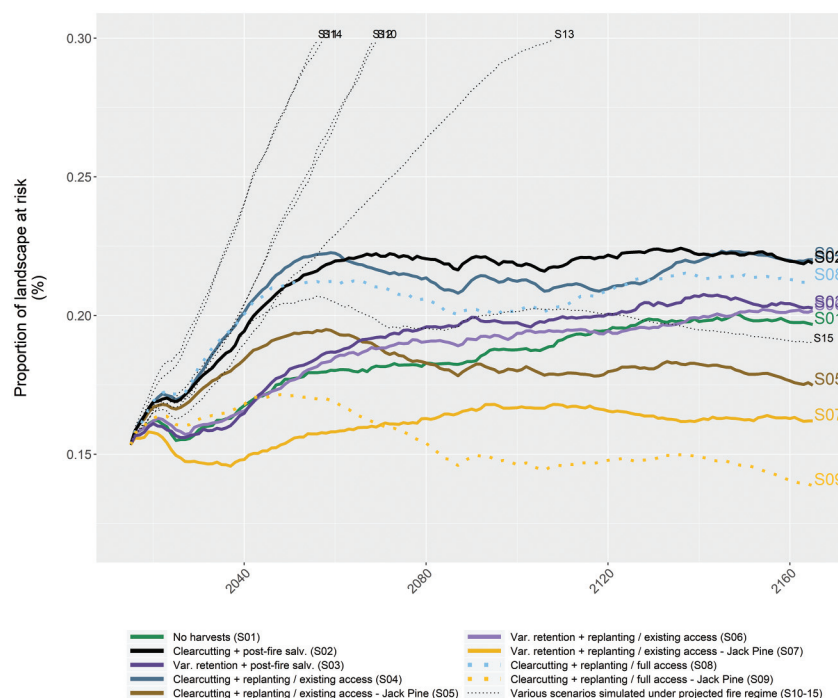
stands were converted to jack pine (S05, S07, and S09; Fig. 4). In fact, conversion to jack pine cover was the most effective treatment to decrease landscape vulnerability. Variable retention scenarios (S06 and S07) also had a greater effect on landscape vulnerability than post-fire reforestation alone. A combination of retention harvesting and conversion to jack pine in sites accessible from the current road network (S07) showed the best results in the early portions of the simulations. In the longer term (after about 55 years), however, the combination of clearcutting and conversion to jack pine in replanted sites with full access (S09) produced the lowest vulnerability (Fig. 4), actually managing to reduce it compared with initial conditions despite a younger age-class structure at the landscape level (result not shown).

Harvested volumes and financial returns under current burn rate scenarios

With regard to cumulated harvested volumes and associated royalties (Fig. 5), all simulated scenarios showed a drop around the 60th year of our simulations (2080), indicating shortfalls in eligible harvestable stands at that moment regardless of the scenario. Under the current fire regime, variable retention decreased the total amount of harvested volumes and associated revenues by about 8.3% to 8.8% when compared with clearcutting.

Costs associated with replanting and road network expansion (when applicable, [not shown]) were far greater in magnitude than the marginal increase in royalties they generated. Consequently, the financial returns were almost entirely driven by the levels of post-fire reforestation efforts (Fig. 5). The scenarios involving no post-fire regeneration failure mitigation efforts (S02 and S03) generated the largest amounts of financial returns and, inversely, the scenarios where all affected stands were replanted showed the smallest financial return (S08 and S09). Scenarios (S02 and S03 vs S08 and S09) were situated on opposite sides of the "break even" line, at comparable distances from it (±400–470 CAN$). Scenarios involving intermediate efforts of post-fire regeneration failure mitigation, i.e., those with reforestation only within the area

accessible using the current road access network (S04–S07), were between those extremes and remained net the break-even line up until timber shortfalls started to occur around 2080.

Scenario comparison under future burn rate

Most of the trends with regard to (1) regeneration failure rates, (2) average potential production, and (3) vulnerability to post-fire regeneration failure observed under a current burn rate scenario were maintained when simulating the considerably higher burn rate projected under RCP 8.5. However, the average proportion of the productive forest area deteriorated at a much higher pace.

In general, the cumulative loss of productive forest area more than doubled under the projected fire regime, ranging from 5.1% to 33.9% (compared to 3.6% to 13.6% under the current burn rate scenario; Table 3). Similar to the current burn rate scenario, the most affected scenarios were those involving clearcutting and no regeneration failure mitigation strategies, while the least affected scenarios were those involving post-fire reforestation of all affected stands in managed areas (S14 and S15). Similarly, average potential production decreased at a much higher rate, especially when no mitigation strategies were implemented, falling from an initial average value of 64.5 m³/ha@120 to 35.9 and 42.1 m³/ha@120 at the 150-year horizon for S11 and S12, respectively, compared to about 50 m³/ha@120 (S02 and S03) under the current burn rate scenario (Table 3). Post-fire reforestation without access constraints allowed to partially mitigate that loss of average potential production (S15), limiting it to 55.1 m³/ha@120 at the end of the simulation horizon, compared to 58.9% under the current burn rate scenarios (S09). The relative abundance of highly productive stands (>80 m³; Table 2) was dramatically reduced in all scenarios simulated under the projected fire regime.

Vulnerability to post-fire regeneration failures also roughly doubled for the most affected scenarios, going from a final value of about 22% of the productive landscape under the current burn rate scenario to 44% under the projected one (see supplementary material 2 - Fig. S2.4[1]). One noticeable difference between both

Fig. 5. Cumulative harvested volume and financial return over the entire simulation period under the current (bold and dashed colored lines) and projected fire regimes (dotted black lines). Each line represents the median of 100 simulations while ribbons encompass 50% of simulations for selected treatments (figure with untruncated *y*-axis in supplementary material 2 - Fig. S2.5[1]). [Color online.]
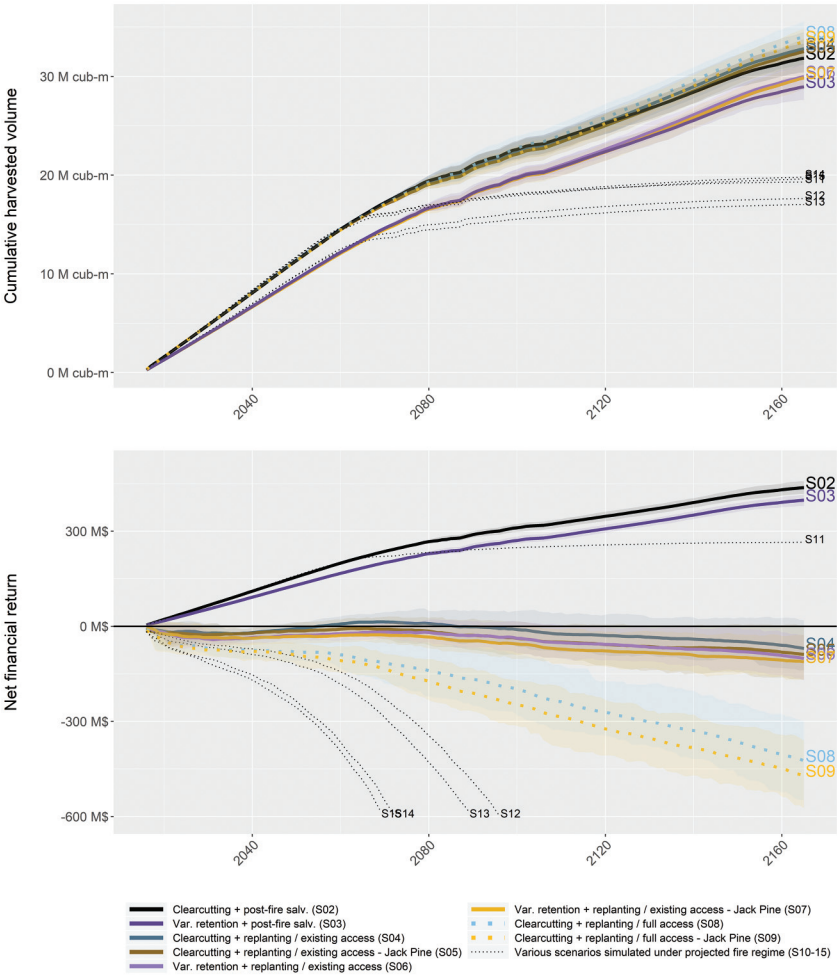

Table 3. Synthesis of outcomes for all assessed regeneration failure mitigation scenarios.

Scenario No.	Cumulative regeneration failure (%)	Median merchantable volume estimated at 120 years of age (m³/ha) at year 150 (percent (%) change)	Mean cumulative volume harvested (Mm³)	Financial returns (CAN$)	Mean cumulative volume harvested (m³/ha)
S01	13.4	57.2 (−11.6%)	N/A	N/A	N/A
S02	13.6	50.1 (−22.5%)	31.8	437.8	38.0
S03	12.0	50.8 (−21.5%)	29.0	398.1	34.7
S04	8.5	53.5 (−17.3%)	32.8	−69.6	39.1
S05	8.3	54.8 (−15.2%)	32.5	−88.3	38.5
S06	7.9	54.1 (−16.4%)	30.0	−101.3	35.8
S07	7.4	55.4 (−14.3%)	29.8	−111.8	35.6
S08	4.0	56.7 (−12.4%)	34.0	−423.9	40.2
S09	3.6	58.9 (−8.9%)	33.5	−470.7	40.0
S10	33.7	35.9 (−44.5%)	N/A	N/A	N/A
S11	33.9	34.9 (−46.1%)	19.3	265.4	22.7
S12	20.0	42.1 (−34.8%)	17.6	−1985.0	20.8
S13	18.7	45.8 (−29.2%)	17.0	−2224.8	20.0
S14	7.6	48.5 (−25.0%)	19.8	−3913.9	23.6
S15	5.1	55.1 (−14.7%)	19.6	−4274.9	23.2

Note: N/A, not applicable.

Table 4. Probability of plantation to reach commercial maturity in the face of current and future burn rate.

| | Current burn rate | | RCP 8.5 |
	Realized	Theoretical	realized
Black spruce	0.392	0.410	0.026
Jack pine	0.448	0.471	0.041

Note: Age of commercial maturity are 90 years old for black spruce, and 76 years old for jack pine. Theoretical probabilities are based on a perfectly constant and spatially homogeneous probability of fire. Realized probabilities were computed directly from simulation outputs.

fire scenarios was that variable retention alone did not produce any substantial improvement when compared with clearcutting (S02 vs S03). Only post-fire reforestation with jack pine, especially with no access constraints, could limit the increase in landscape vulnerability to a certain extent.

In terms of financial returns, the level of post-fire reforestation effort remained the most important driver, with even higher associated costs. Consequently, all scenarios involving post-fire reforestation rapidly dropped into deficit, and ended up with an accumulated deficit almost 10 times larger than for the current burn rate scenarios (Table 3).

Proportion of plantations reaching commercial maturity

In all simulations, the chances of plantation surviving long enough to reach commercial maturity was relatively low. Under the current burn rate scenarios, the probability of black spruce plantation reaching its 90 years old age of commercial maturity was just below 40%, while it was near 45% for jack pine (commercially mature at 76 years old; Table 4). Those probabilities were much lower under the projected RCP 8.5 fire regime; 2.55% and 4.14%, for black spruce and jack pine, respectively. The realized probabilities were slightly lower than the theoretical ones, which were calculated based on a perfectly constant and spatially homogeneous probability of fire.

Discussion

In Canada, regeneration monitoring systems are generally designed to assure that appropriate actions are taken to maintain or improve regeneration density after harvesting (Natural Resources Canada 2020). In contrast, there is usually no mandatory monitoring of regeneration after natural disturbances such as fire. Strategic forest management planning typically assumes that post-fire stand development follows the same age-dependent trajectory as prior to the fire. It is often only a number of decades later, when stands reach some re-entry height threshold, that forest inventories describe forest cover again, and update stand attributes as necessary. By explicitly simulating post-fire regeneration density and immediately updating the parameters used to project future growth and yield, we project considerable impacts of regeneration failure on long term forest productivity (landscape and stand levels) and, consequently, on ecosystem services provisioning.

We focused on exploring a large number of scenarios integrating the stochasticity inherent to fire disturbances and thereby chose to use a relatively coarse resolution. That prevented us from integrating ecological processes that operate at scales finer than that of a single cell (25 ha), such as variable fire severity (Baltzer et al. 2021) and residual patches (Kafka et al. 2001; Krawchuk et al. 2020), which play important roles in the post-fire regeneration dynamics. We did not integrate any direct effects of climate change on stand productivity and, therefore, did not adjust the time required to reach sexual or commercial maturity accordingly. There is still no consensus, however, as to whether climate change will increase or decrease productivity in that area and in other fire-prone boreal regions (Girardin et al. 2016; D'Orangeville et al. 2018; Chaste et al. 2019; Boucher et al. 2020). Future work would certainly benefit from

taking those aspects into consideration. Nevertheless, the value of our approach resides in providing first projections of productivity losses that could occur in fire-prone boreal regions with forest management and highlighting the necessity to anticipate these risks so that early actions can be taken. It also allows the comparisons of different means to mitigate those risks in terms of some costs and benefits.

Our results show that indicators such as the ones used here are needed to assess the impact of regeneration failure early in terms of losses in productive areas over time and space. In fact, under the business-as-usual scenario after 150 years, 13.6% of the initially productive forested area would become unproductive. Such a rate of post-fire regeneration failures is comparable or lower than those observed in previous empirical (Girard et al. 2009; Baltzer et al. 2021) and modeling (Splawinski et al. 2019b) studies, suggesting that our results might be conservative. Baltzer et al. (2021) also show how widespread this phenomenon is across the boreal forest of North America and suggest that the observed loss of post-fire resilience is symptomatic of large portions of the boreal system moving toward a tipping point that has not been crossed in several thousands of years.

While fire activity is the main driver of productive area loss, harvesting also contributes indirectly to post-fire regeneration failure by increasing the amount of young and vulnerable stands within the landscape. Combined with the effects of fire, harvesting the most productive stands and selectively bringing them back within their window of vulnerability with regards to post-fire regeneration failure produced substantial drops in the amount of stands of interest for the forest industry (≥50 m^3/ha@120), particularly the most productive ones (≥80 m^3/ha@120). That trend is coherent with the recently observed decline in mean diameter of harvested timber in Quebec (Coulombe et al. 2004; Bureau du forestier en chef 2013) that could lead to sparser regeneration and reduced productivity (Splawinski et al. 2014).

Altogether, both types of productivity erosion (loss of productive areas and decrease in average stand productivity) led to timber shortfalls after 60 years of simulation in our study area, in large part due to past practices that did not foresee such productivity losses (Raulier et al. 2013; Leduc et al. 2015; Schab et al. 2021), a result that also replicate that of another prospective simulation study (Bureau du forestier en chef 2020). Even in the scenarios of reforestation with full road access, the level of highly productive forests (≥80 m^3/ha@120) was still lower than at the beginning of the simulation, suggesting a legacy of past actions/inaction that might already have set the process in motion by shifting the landscape mosaic towards a younger and more vulnerable one. Therefore, the post-fire regeneration failure mitigation strategies that we investigated might not only be of importance for maintaining forest productivity, but might be necessary should we aim to restore historic levels of productivity and resilience.

Mitigation strategies of productivity losses, landscape vulnerability, and probabilities of plantation to reach commercial maturity

We examined two adaptive means of mitigating losses in forest productivity, one reactive strategy consisting of reforestation of stands affected by post-fire regeneration failure, with associated species selection, and a proactive strategy consisting in variable retention harvesting. Post-fire reforestation is the most effective strategy to maintain or even increase landscape productivity. However, in boreal landscapes where the overall productivity is generally low and financial returns are already marginal, costs associated with this strategy would likely exceed revenues, particularly in situations where new roads have to be constructed and maintained. Moreover, the chances that such plantations burn before reaching commercial maturity is considerable thereby reducing the probability of a return on investment. For

instance, Splawinski et al. (2019*a*) showed that in conditions typically encountered in boreal areas of Quebec and under a conservative costs scenario, plantation of black spruce could only be made profitable if the mean fire return interval is over 300 years. It should be recalled that the financial return should not be mistaken for the result of a complete *economic* analysis, which differ in its treatments of external effects such as subsidies, jobs and intangible strategic benefits like land occupancy, that also contribute to social welfare (International Fund for Agricultural Development 2015). Moreover, none of the resulting values were discounted, implying that revenues and costs over time were valued on the same level as those in the near future, contrary to usual practices (Bureau du forestier en chef 2013). It should thus be considered as one of several indicators allowing the comparisons of various scenarios.

Converting black spruce dominated stands to jack pine plantations is a more proactive strategy, the latter species being better adapted to higher burn rate since it both grows and reaches sexual maturity faster than black spruce (Viglas et al. 2013; Briand et al. 2015), and is thought to be more resilient to projected future conditions such as elevated fire intensities (Gauthier et al. 1996, 2014; De Groot et al. 2004; Baltzer et al. 2021) and increased drought (Rudolph and Laidly 1990; Viereck and Johnson 1990; Marchand et al. 2021). This approach would therefore improve the chance of a positive return on plantation investment.

The probabilities of plantations to reach commercial maturity realized in our simulations were systematically lower than those calculated using constant and homogeneous burning probabilities. In fact, although our model adequately achieved our target burn rate values, fires did not burn the forested landscape in a perfectly random manner. The spatial configuration of non-flammable land cover (mostly lakes and rivers) and flammable ones influenced the local probability of burning; cells that were surrounded by a higher number of flammable neighbors had a higher probability of burning than those surrounded by firebreaks. That emergent property highlights the effect that water bodies (Mansuy et al. 2014; Erni et al. 2017) and surficial deposits (Mansuy et al. 2010) have on fire propagation by acting as total or partial firebreaks. In real life situations, where probabilities of burning cannot be expected to be perfectly homogeneous, stands affected by post-fire regeneration failure are likely to be part of a subset of the landscape that burn more often; therefore, it may be optimistic to estimate the chance of plantations reaching commercial maturity based on average burn rate. It could also be argued that because the probability of burning was not dependent on fuel characteristics such as cover type and stand age in our model (Bernier et al. 2016; Erni et al. 2017), the probability of burning in young plantations and the regeneration failure areas in general might be overestimated. The extent to which that negative feedback from the vegetation limits fire activity, however, depends on the overall burn rate. Extreme burn rates which are strongly dependent on fuel age, i.e., <50-year mean fire return interval (Héon et al. 2014), are only reached towards the second half of the 21st century in our simulations under RCP 8.5. In such situation, very young stands still burn at a rate that can reach over 1% annually (Héon et al. 2014; Erni et al. 2017). Under lower burn rate, the probability of burning mostly differs between stands younger than 30 years old (burn slightly less), and older ones (Héon et al. 2014; Bernier et al. 2016). This young age-class (<30 years old) is well below the 50–60 years required for the average stands to accumulate a seed bank large enough to successfully regenerate a stand of equal productivity in the study area, and even shorter than the 76–90 years required to reach commercial maturity. Consequently, the absence of such a negative feedback in our fire model would not significantly affect our estimates of plantation survival and regeneration failure areas under the baseline scenario. Our current burn rate scenarios, therefore, represent the lower boundary of an uncertainty envelope, as they are an unlikely future where fire activity remains comparable to that observed in recent history, and where the fuel age – burn rate relationship is minimal. At the other end of the spectrum, the fire regime projected under RCP 8.5 provides a more pessimistic and extreme portrait of the future, which might not materialize as rapidly as simulated, if at all, because of negative feedback from vegetation was neglected, but which allows identifying limits in similar managed systems and in our means of actions.

The variable retention strategy can also be considered as a proactive approach that aims, among other things, at reducing the vulnerability of regeneration failure due to future fires. It requires retaining a fraction of the standing timber volume, hence providing the aerial seedbank that improves chances of successful natural regeneration in the event of a subsequent fire, but does not require the construction and maintenance of additional roads throughout the forest management unit over time. The implementation of such a strategy results in a lower overall productivity of the FMU, as stand productivity is not systematically restored in case of regeneration failure, but the costs are lower. It also has the advantage of being an opportunity cost rather than an explicit one. In addition, it clearly reduces the vulnerability of the FMU to future fires, particularly when combined with jack pine plantations around the current road network. In fact, it can be contrasted with the reforestation strategy, in which the investment in plantation has limited chances of coming to fruition, particularly under the projected RCP 8.5 burn rate. The important contribution of variable retention to biodiversity conservation (Beese et al. 2019) should not be overlooked as another advantage of this strategy.

Conclusion

Our study stresses the importance to integrate fire a priori in strategic forest management planning (e.g., Savage et al. 2010; Leduc et al. 2015). Integrating fire-related risks a posteriori by adopting the current rolling-horizon re-planning approach creates a systematic divergence between the planned and the actual system state trajectories, which is responsible for the drift towards a less productive state of the forest (Paradis et al. 2013). Our study also demonstrates the usefulness of indicators of potential production and landscape vulnerability that allows to better anticipate future variations in productivity and, consequently, in harvest volumes.

In summary, a passive management of regeneration failure leads to an overestimation of future productive areas and average stand productivity, resulting in an overestimation of the available timber supply. Moreover, although logging alone is not directly responsible for significant losses in productive forest areas, harvesting of mature and productive stands in a fire-prone environment leads to a significant decrease in the average potential production at the landscape and stand levels. While extensive post-fire reforestation could be the most effective strategy in terms of maintaining and improving landscape productivity, such strategy will quickly become prohibitive because of the associated costs and low return on investments due to high probability of plantations re-burning. More proactive strategies such as a more extensive use of variable retention harvesting, combined with replanting of fire adapted jack pine in areas easily accessible from the existing road network, appears as a promising approach, as both direct costs and overall vulnerability of the landscape to future regeneration failure events are lower.

Our projections of substantial long-term negative impacts of post-fire regeneration failure on forest productivity highlight the importance of implementing better monitoring of post-natural disturbance regeneration, similar to what is done in harvested sites. Early detection of regeneration failure would expedite intervention via silvicultural treatments and (or) adjustments to strategic forest planning; it would also provide further empirical data on the phenomenon, thereby improving understanding and response capacity.

Acknowledgements

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