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Future fire risk and the greenhouse gas mitigation potential of forest rehabilitation in British Columbia, Canada

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ABSTRACT

Increased forest fires in the future will create opportunities to undertake salvage logging and replanting activities with the potential to reduce greenhouse gas (GHG) emissions relative to a 'do nothing' scenario that relies on natural regeneration. Salvage logging of fire-killed wood will generate additional useful products for society while replanting will provide opportunities to establish seedlings with genetic gain and increased climate resilience. In British Columbia, Canada, our study showed that cumulative net GHG benefit from these rehabilitation activities on about 14 % of the area burned ranges from –32 to −79 $MtCO_2e$ in 2070, but cumulative net GHG reduction benefits are not realized for 23 to 31 years due to the emissions debt that is incurred from harvest wood product emissions and residue management. Scenarios were modelled using the Generic Carbon Budget Model (GCBM) that tracked carbon in the forest and a harvested wood products model that tracked the fate of C and the substitution benefits achieved through wood use, both developed by the Canadian Forest Service. Results were evaluated across 100 simulations of future fire, developed using a log-normal model fit to historic fire events and an assumption of linearly increased area annually burned by 2070 to double the average of the period 1950 to 2018. Our results suggest that mitigation efforts might be better directed at reducing wildfire risks and emissions in the first place, rather than rehabilitating post-fire outcomes.

1. Introduction

Forests remove carbon (C) from the atmosphere and store it in the ecosystem as vegetation, dead organic matter (DOM), and soil and release C through respiration and wildfire emissions (Kurz et al., 2013). Humans manage forest ecosystems to provide society with a wide range of products, balancing this with the need to maintain forest habitats and a diversity of ecosystem services. Sustainable forest management has become more complex as ecosystems respond to a changing climate and, over the coming decades, management will become increasingly more challenging as climate change impacts on forests increase (Halofsky et al., 2018). The role of forests in the global carbon cycle and using forests to contribute to mitigating climate change will also require consideration (Lemprière et al., 2013), as governments and society aim to achieve net zero and net negative emissions. Improved forest management approaches that increase carbon sequestration or avoid emissions in the forest sector are among a suite of potential natural climate solutions that Canada could use to achieve this goal (Drever et al., 2021).

Wildfire is a mitigation risk because burning causes large direct and delayed emissions of greenhouse gases (GHG). Forests take time to regrow and become a net sink of C (Kurz et al., 2013). British Columbia (BC), Canada's western-most province, contains about 61 Mha of forest (Fig. 1). The area burned by wildfire in 2017 and 2018 (greater than1 million ha) both exceeded the previously observed maximum of 0.82 million ha in 1958 (Hanes et al., 2019).. Previous analyses identifying potential mitigation activities and portfolios for Canada (Smyth et al., 2014; Smyth et al., 2017a) and BC (Smyth et al., 2020) identified that the quantification of future wildfire risk as a key modelling improvement, particularly in light of the 2017 and 2018 fire years in BC. However, wildfires are also an opportunity because rehabilitating severely burned stands is an improved forest management activity that could contribute to mitigating climate change.

In a previous study, Metsaranta et al. (2011) (hereafter M11) examined the potential effects of changes in wildfire area burned, forest productivity, and decay rates of soil and DOM on the future C dynamics

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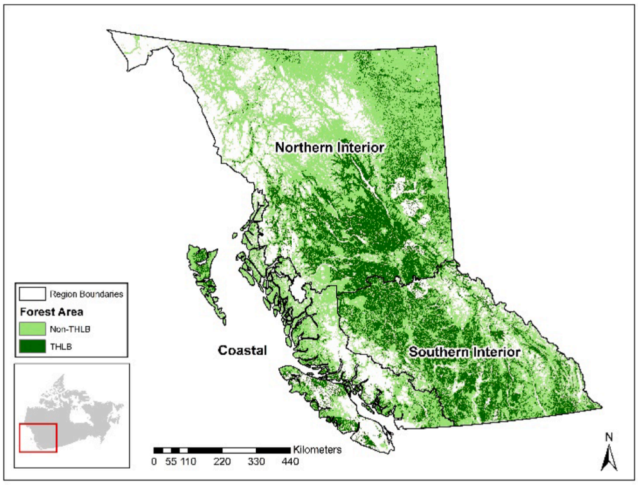

Fig. 1. The province of British Columbia, with inset showing its location in western Canada. The map shows the three regions, Coast, Northern Interior, and Southern Interior, used for projecting future area burned, as well as the distribution of the timber harvest (THLB) and non-timber harvesting (Non-THLB) landbase. Rehabilitation was assumed to occur only in the THLB. White areas are non-forest or areas with no accessible forest inventory data.

of BC forests to 2080, concluding that a wide range of outcomes was possible, depending on the magnitude and direction of ecosystem responses. The analysis used Monte Carlo simulation to assess risks of potential fire futures based on historical burned area that did not include the recent extreme fire years 2017–18 because they had not yet been observed. The results were also based on Canada's National Forest Carbon Monitoring Accounting and Reporting system of that era (Kurz and Apps, 2006; Kurz et al., 2009; Stinson et al., 2011; Metsaranta et al., 2017), when only a simplified, spatially-referenced representation of BC forests could be projected. Following Canada's forest C science blueprint (Bernier et al., 2012), improvements to modelling systems and data now allow increased spatial representation. In addition, a detailed representation of the fate of C in harvested wood (HWP) is now included. Understanding the fate of C in HWP, and the degree to which these products substitute for more C intensive alternatives is critically important to assessing the climate mitigation benefits of forest management (Lemprière et al., 2013; Smyth et al., 2014; Smyth et al., 2017b; Leskinen et al., 2018; Xu et al., 2018, Hurmekoski et al., 2021).

This paper used Monte Carlo simulation-based assessment of future fire risk and spatial modelling to examine two objectives. The first is to evaluate options for post-disturbance rehabilitation that could increase C sequestration in BC forests after disturbance, and to compare this GHG reduction to GHG emissions from wildfire. A second aim is to discuss some challenges associated with quantifying and forecasting changes in future annual area burned, which is critical to quantitatively describing risks to forest carbon stocks and the GHG mitigation potential of forests. This topic received little coverage in a recent review of wildland fire risk research in Canada (Johnston et al., 2020), but is of key importance as society embarks on natural climate solutions for mitigating climate change (e.g. Drever et al., 2021), some of which could take place in fire prone areas that are at risk of burning.

2. Methods

2.1. Carbon modelling

The Generic Carbon Budget Model (GCBM), built on the open-source platform of the Full Lands Integration Tool (FLINT) developed and maintained by moja global[1], generated the ecosystem C forecasts. The GCBM currently uses the same structure, equations, logic, and default assumptions of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3 Kurz et al., 2009), but in a spatially-explicit modelling environment. Briefly, the CBM-CFS3 uses mainly forest inventory, yield table, and disturbance data as input. Whole ecosystem C is tracked in 10 live biomass and 11 soil and dead organic matter (DOM) pools at annual time steps. Aboveground biomass for each softwood (gymnosperm) and hardwood (angiosperm) species estimated from merchantable wood volume over age (m^3 ha^{-1} $year^{-1}$) yield tables (Boudewyn et al., 2007) and belowground biomass from aboveground biomass C (Li et al., 2003). Annual rates (% $year^{-1}$) of model biomass turnover are assigned to detrital C pools with litterfall transfer parameters. Soil and DOM C pools decompose with pool specific mean annual temperature dependent annual decay rates. Decay releases some C directly to the atmosphere. The remaining C is transferred to a slowly decomposing pool from which further decay releases all C to the atmosphere. Repeated iterations of growth and stand-replacing disturbance that terminate when the difference between total C in slowly decaying pools in successive iterations is < 0.1 %. are used to initialize soil and DOM C pools. Disturbance impacts are simulated by matrices defining proportional C between pools and fluxes to the atmosphere or forest products. To estimate direct fire emissions in units of CO_2e, we applied 100 year Global Warming Potentials of 25 for CH_4 and 298 for N_2O (IPCC 2007).

The BC Ministry of Forests (FOR) provided the forest inventory and yield curves (TASS-TIPSY and VDYP7)[2], which are not sensitive to environmental changes. The model was run from 1990 to 2070 for 61.5 million ha of public forests at (0.001 degree) (~1 ha) resolution. Forests in BC are subdivided into a timber harvesting (THLB, 36 % of forest area) and non-timber harvesting (nonTHLB, 64 %) landbase. Forest management activities generally occur only on the THLB, and the areas designated as harvestable can change over time. The circa 2015 forest inventory was rolled back to represent the age structure of forests in 1990 (Morken et al. 2022). The historical part of the model runs used observed harvest, wildfire, and insect disturbance data. Harvest projections started in 2015, fire projections in 2019, but no insect outbreaks were projected. Harvested wood was transferred to the HWP sector and used to produce various commodities (pulp, paper, panels, dimensional lumber and bioenergy) and substitute for other products. A harvested wood products model tracked C through manufacturing, export, use, and post-consumer treatment using a simple decay approach run on an Abstract Network Simulation Engine (ANSE v1). The model and parameters are consistent with Smyth et al. (2020), and include 4 commodity types (sawnwood, industrial roundwood, panels, and pulp and paper with default half lives of 35, 35, 25 and 2 years, respectively), and mill residues which are assumed to be burned for energy. Post-consumer commodities were incinerated, or burned for energy, or sent to landfills where a portion (0.6) was assumed degradable and released carbon dioxide and methane emissions, some of which was flared or used for energy. The substitution benefits are also consistent with Smyth et al. (2020). Bioenergy from burning mill residues had a substitution benefit of 0.5 tCO2e of fossil emissions avoided per 1 tCO2e of bioenergy produced. For products, modest substitution benefits for sawnwood (0.54 tC avoided per 1 tC of sawnwood used) and panels (0.45 tC/tC for panels) were assumed. Pulp and paper use was assumed to not contribute any substitution benefits (but see also for example Achachlouei and Moberg, 2015). Further details are in 2.3, 2.4, and Smyth et al. (2020).

2.2. Future area burned scenarios

Area burned data were from the National Fire Database (1950–1985,

[1] https://moja.global.

[2] https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory/growth-and-yield-modelling.

NFDB, Hanes et al., 2019)[3], the National Burn Area Composite (1986–2017, NBAC, Hall et al., 2020)[4], and the BC Historical Fire Burn Severity dataset (2018 only)[5]. A log-normal distribution with parameters estimated from observed area burned (1950–2018) was used to generate future area burned forecasts statistically consistent with observations (Armstrong, 1999) and adjustable for future scenarios (Metsaranta, 2010). A log-normal distribution has parameters μ and σ that are the mean and standard deviation on a logarithmic scale, and density function:

$$f(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}}e^{-\frac{(ln(x)-\mu)^2}{2\sigma^2}} \tag{1}$$

Future area burned in Canada will increase (Flannigan et al., 2005; Krawchuk et al., 2008; Balshi et al., 2009; De Groot et al., 2013; Schoennagel et al., 2017), and M11 assumed future mean area burned would double, which is still a reasonable assumption for BC (Kirchmeier-Young et al., 2019)[6]. A lognormal distribution has mean:

$$E(X) = e^{\mu+\frac{1}{2}\sigma^2} \tag{2}$$

This analysis doubled the mean linearly from 2020 to 70 by changing μ and holding σ constant. Other adjustments that also change *E(X)* to 2*E(X)* have similar but not identical results (Metsaranta, 2010). Maximum annual area burned was limited to twice the historical maximum, also assumed to double over time. Individual fires (minimum 100 ha) were generated from a second log-normal distribution fit to the fire size data and distributed randomly onto publically owned forests (95 % of the forest area) assuming ellipsoidal shapes and no re-burning for 10 years, stopping when the sum equalled the total required annual area burned.

2.3. Evaluation of area burned projections

Table 1 reports μ and σ for combinations of region, observational period, and assumed change in mean. The forecasts subdivided BC into Coast, Northern Interior and Southern Interior regions (Fig. 1), and assumed that the mean area burned increased linearly from the 1950–2018 observed mean to the 1950–2018 doubled mean over the period 2020–2070. Fig. 2A shows area burned in BC from this study and M11 (which used 1950–2005 data, 13 fewer years than the current analysis and missing the 2017–18 extremes), as well as the area that has subsequently burned from 2019 to 2021[7], that was not used to estimate the lognormal parameters in the C forecasts of either study. In hydrology, estimates of the riverine floodplain covered during 100-year floods, termed the return period, figure prominently in environmental regulation (Milly et al., 2008). Similar concepts have not commonly been used in wildfire risk assessment. Return periods are a measure that indicates the average frequency with which an event of a particular severity is expected to occur in the future, and can be extrapolated to estimate the probability of as-yet unobserved extreme years (Metsaranta, 2010). We conducted additional analyses that explored uncertainties in the area burned projections. Rather than evaluating central tendencies, these analyses examined the estimated frequency and magnitude of large fire years because extreme events influence conclusions regarding forest sustainability to a degree that has not previously been appreciated (Nelson and Scorah, 2021). The statistics were the annual area burned (ha) expected to occur on average once every 100 years (100-year area burned) and the expected average frequency (years) that 1 million ha is expected to burn in one year in the future (1 million ha return period). A value of 1 million ha was chose because this is the threshold exceeded in 2017 and 2018 for the first time in the historical record. The two statistics are inversely related: when extreme values are more likely, then the 100 year area burned will increase and the 1 million ha return period will decrease. Fig. 2B plots annual areas burned in British Columbia with expected return periods from 1 to 300 years under four possible scenarios of future area burned, derived from two different observation periods (1950–2005 as in M11 and 1950–2018 as in this study), and two assumptions about the future mean (observed or doubled) (Table 1). Return periods were estimated using methods for lognormal data in Rao and Hamed (2000). The 100-year area burned under these four scenarios, which also assume that area burned is independent of landscape characteristics, ranges from 0.67 (1950–2005 observed mean) to 3.14 (1950–2018 doubled mean) million ha (Fig. 2B). Estimates from the 1950–2005 doubled mean and the 1950–2018 observed mean are similar (100-year area burned 1.34 and 1.56 million ha), respectively.

We first examined how the estimated values for these statistics have changed over time in the past, as each additional year of data has accrued since 1980. This analysis included the additional observations from 2019 to 21, that were not used to develop the area burned projections used in the C forecasts. Lognormal distributions were fit to the time series each year from 1980 to 2021, using the *fitdist* function in the *fitdistrplus* package for R, and then 100-year area burned and the 1 million ha return period were calculated from the estimated μ and σ following Rao and Hamed (2000). Uncertainty for past estimates of the two statistics was determined from the 10th and 90th percentiles of the distribution (80 % confidence interval) of 10,000 bootstrap estimates of the lognormal distribution parameters using the *bootdist* function in *fitdistrplus*. The second analysis estimated the variation in 100-year area burned and 1 million ha return period that could be observed in 2070, under three different fire futures derived from the 1950–2021 observations: observed mean, a step doubled mean in 2022, and a mean that gradually doubles from 2022 to 2070 (Table 1). A gradually doubling mean is consistent with the assumptions used in the C forecasts. Each

Table 1
Log-normal parameter estimates for different fire futures, based on region of British Columbia, Canada, time periods of observation, and assumption about future mean area burned (kha/yr).

Fire future[a]	μ (SE)[c]	σ (SE)	Log-normal mean (kha/yr)
1950–2018 observed mean, British Columbia	10.70 (0.18)	1.53 (0.13)	144
1950–2018 observed mean, northern interior	10.17 (0.20)	1.64 (0.14)	100
1950–2018 observed mean, southern interior	8.71 (0.24)	2.02 (0.17)	47
1950–2018 observed mean, coast	6.84 (0.23)	1.89 (0.16)	5.5
1950–2018 doubled mean, British Columbia	11.40	1.53	288
1950–2018 doubled mean, northern interior	10.86	1.64	199
1950–2018 doubled mean, southern interior	9.41	2.02	93
1950–2018 doubled mean, coast	7.53	1.89	11
1950–2005, observed mean, British Columbia[b]	10.40 (0.17)	1.30 (0.12)	76
1950–2005, doubled mean, British Columbia[b,c]	11.09	1.30	151
1950–2021 observed mean, British Columbia	10.72 (0.18)	1.55 (0.13)	150
1950–2021 doubled mean, British Columbia[c]	11.41	1.55	299

[a] In the C forecasts, the mean increased linearly 2020–70 from the 1950–2018 observed to the 1950–2018 doubled mean.
[b] Provided for comparison to M11.
[c] Standard error is not available for doubled mean distributions because they are assumed, not estimated from data.

[3] https://cwfis.cfs.nrcan.gc.ca/datamart.
[4] https://cwfis.cfs.nrcan.gc.ca/datamart.
[5] https://catalogue.data.gov.bc.ca/dataset/fire-burn-severity-historical.
[6] See also Wallenius et al. (2011) and Meyn et al. (2013) for other interpretations before 2017–18.
[7] 2019–21 data in Fig. 2A were retrieved from the NBAC, after the analysis had been completed.

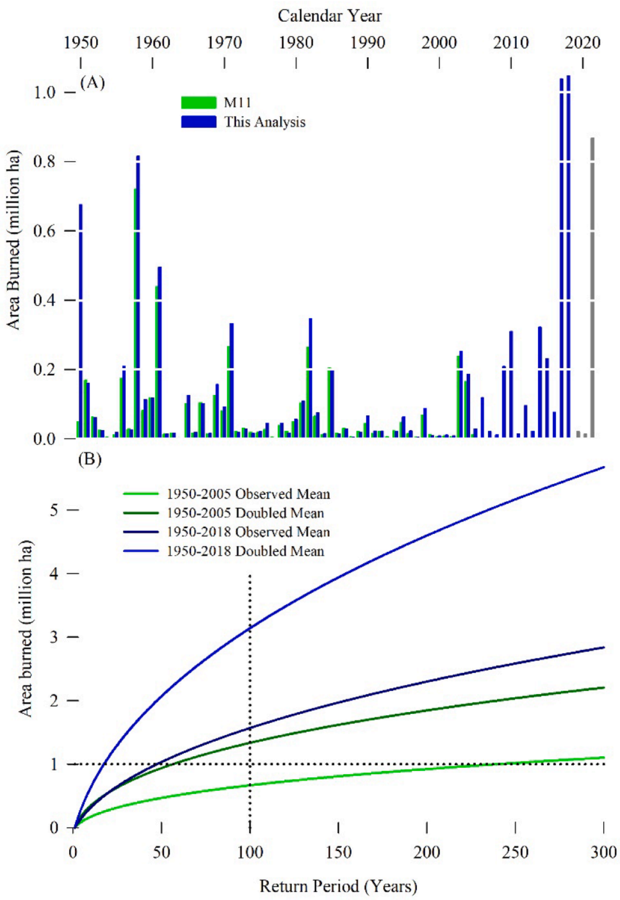

Fig. 2. Area burned in British Columbia, Canada, in the present study (blue, 1950–2018), in the study of Metsaranta et al., (2011, M11)(green, 1950–2005) and subsequent observations not used in either study (grey, 2019–2021) (A), and areas burned (million ha) with return periods of 1 to 300 years under four fire futures (1950–2005 or 1950–2018 observations and observed or doubled means, Table 1) (B). The horizontal dashed line shows 1 million ha. The corresponding expected return period for 1 million ha may be read off the x-axis from the point at which this horizontal line crosses each curve. The vertical dashed line shows 100 years. The corresponding area expected to burn on average once every 100 years may be read off the y-axis from the point at which this vertical line crosses each curve. A change occurred to the 1950 burned area estimate since M11 was published. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

future was simulated 10,000 times from 2022 to 2070. At the end of the simulation, 100-year area burned and 1 million ha return period were calculated from the combined observed (1950–2021) and simulated (2022–2070) time series. The 80 % and 95 % distributions of these simulations were used to infer the degree of statistical overlap between the predictions of these three scenarios that could be observed in 2070. Finally, we also examined possible areas burned that could be observed in the short term future. The questions examined were, (1) the probability of exceeding in the 5 years from 2022 to 2026, a total area burned larger than the total area that burned in the 5 years from 2017 to 2021, and (2) the probability that one of the 5 years from 2022 to 2026 would exceed 1 million ha. Both of these probabilities were calculated from 10,000 simulated 5 year time series, using either the 1950–2021 observed mean or the 1950–2021 doubled mean lognormal parameters (Table 1).

2.4. Rehabilitation

The climate mitigation potential was determined by comparing scenarios with (REHAB) and without (BASE) burned stand rehabilitation. Fire location, size, and emission factors (CBM-CFS3 disturbance matrices Kurz et al., 2009), as well as initial species, age class, and C content of the forest in 2020 were the same in both scenarios. Post-fire stands that were not rehabilitated, which included all stands in BASE and unsuitable stands in REHAB, used unmanaged growth curves from VDYP7 and were assumed to regenerate back to pre-fire conditions with no regeneration delay and unburned material decaying in situ. In the REHAB scenario, selected sites instead receive rehabilitation treatments in the same year as the fire. The sites selected for rehabilitation were in the THLB, within 500 m of a road, with site index (SI) ≥ 15 m height at age 50 years, and consisted of softwood species plus alder. Rehabilitation consisted of salvage harvesting, in situ burning of harvest residues for fire risk management on some sites, and planting genetically improved seedlings that shifted sites to managed growth curves from TASS-TIPSY. Salvage logging was in addition to regular harvest and did not reduce green tree harvest, which if implemented would yield additional mitigation benefits (Smyth et al. 2014). Residue burning was carried out after harvest at rates (i.e., the proportion of harvested areas subsequently burned) adjusted to be consistent with BC's reported slashburning emissions (Environment and Climate Change Canada, 2019). These rates differentiated coastal regions which have lower rates of residue burning from the interior. Residue burning released to the atmosphere 10–20 % of the C in dead stems, branches, coarse and fine woody debris, and foliar litter that remained after salvage harvest. Salvage utilization of burned stem-wood was 75 % (due to thicker bark) for Douglas-fir (*Pseudotsuga menziesii*) and 50 % for other species.

The five species planted at rehabilitated sites (lodgepole pine (*Pinus contorta*, 54 %), white spruce (*Picea glauca*, 21 %), Douglas-fir (7 %), western redcedar (*Thuja plicata*, 9 %), and Engelmann spruce (*Picea engelmanii*, 9 %) were representative of recent commercial practices. BC provided managed growth curves that represent modern seedlings with genetic gain and increased resilience to drought and insects, understood to have been modelled using TASS/TIPSY and supported by Young Stand Monitoring[8] (YSM) program data. Only genetic gain would affect C outcomes (through higher yield) because the forecasts did not include future drought and insects. Growth curves consisted of multiple curves for different species in each unique combination of Biogeoclimatic Ecosystem Classification (BEC) zone and SI class, which were aggregated into a single curve for each BEC and SI combination (weighted by planting occurrence data also provided by BC) for C modelling. The pre-existing BEC zone and SI class determined the post-rehabilitation yield curve. Douglas-fir and western redcedar had "high" yield, defined as having improved yield greater than about + 85 m^3 at 40 years compared to the original yield curve; other species, not included in the "high" yield definition, were defined as having "moderate" yield.

2.5. Ecosystem C and GHG mitigation indicators

We analyzed wildfire disturbance emissions and the net GHG change from rehabilitation activities. The impact of the current study's more severe wildfire future is assessed by comparing wildfire emissions to the most similar scenario in M11. The net GHG change from rehabilitation activities, relative to a do nothing baseline (REHAB – BASE), was quantified using a systems approach in which we consider changes in ecosystem emissions and removals (i.e., NBP), emissions and carbon storage from salvage harvested wood products put into use, and their associated substitution benefits from using mill residues for bioenergy

[8] https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory/inventory-analysis-reports/provincial-monitoring-reports.

and avoiding fossil fuel burning, and the use of wood products in place of emissions-intensive materials. In other words, the analysis included carbon stored in the whole ecosystem (aboveground biomass, below-ground biomass, deadwood, litter, and soil), carbon stored in forest products, and substitution effects. A negative value in the net GHG change represents a net reduction of emissions to the atmosphere due to rehabilitation activities.

The results present the median (50th percentile) and the 10th and 90th percentiles (80 % confidence interval) of cumulative totals between 2020 and 2070 for 100 Monte Carlo simulations with varying future area burned as described in section 2.2. The net GHG change for rehabilitation was estimated overall, and was regionally differentiated according to (i) interior and coastal residue management, (ii) species-differentiated salvage harvest utilization rate and, (iii) planted stand yield (high or moderate). These factors (interior/coastal, Douglas-fir/non-Douglas fir, high/moderate yield) were used to create a spatial mask (i.e., a specific collection of pixels that represents a combination of those factors) that was intersected with the spatially-explicit carbon fluxes produced by GCBM to assess the impact of the various combinations of factors. The carbon impact of harvested wood products and substitution benefits was also included and was assigned to the pixel from which the harvested wood originated. This assignment was based on statistical averages not chain-of-custody tracking of the harvested wood.

3. Results

3.1. Future area burned and rehabilitated

Median 2020–70 cumulative area burned for the doubling mean distribution (used in the C forecasts) was 10.68 (80 % 7.86–15.58) million ha and 6.99 (80 % 5.45–10.79) million ha for the observed mean distribution (Fig. 3A). Median 2020–70 cumulative area rehabilitated was 1.49 (80 % 1.02–2.24) million ha (Fig. 3B), 13.67 % (80 % 12.37–15.97 %) of the cumulative area burned. When more area burned, more area was rehabilitated ($r^2 = 0.87$).

3.2. Future wildfire emissions

Annual direct wildfire emissions were highly variable (Fig. 4A). Median annual direct wildfire emissions increased over time from 16.2 $MtCO_2e$ (80 % 3.3 to 70.0 $MtCO_2e$) in 2030 to 24.1 $MtCO_2e$ (80 % 6.0 to 127.9 $MtCO_2e$) in 2070 (Fig. 4A). Median cumulative direct wildfire emissions 2020–70 were 2.26 $GtCO_2e$ (80 % 1.65 to 3.26 $GtCO_2e$), about twice the estimate from M11 (1.14 [80 % 0.89 to 1.51] $GtCO_2e$, Fig. 4B). THLB (0.77 [80 % 0.56 to 1.12] $GtCO_2e$, 35 % of the total) and non THLB (1.47 [80 % 1.11 to 2.13] $GtCO_2e$, 65 % of the total) cumulative direct emissions were roughly proportional to the area of forest in the THLB and non THLB because fire was assumed spatially random.

3.3. Mitigation potential of rehabilitation

Rehabilitation was implemented over a median cumulative area of 216 (80 % 110–411) kha by 2030, 755 (80 % 516–1155) kha by 2050, and 1486 (80 % 1020–2237) kha by 2070. This increased median cumulative net GHG emissions by 2.40 (80 % 1.21 to 5.04) $MtCO_2e$ in 2030, decreased median cumulative net GHG emissions by −3.09 (80 % −9.05 to 1.18) $MtCO_2e$ in 2050, and further decreased median cumulative net GHG emissions by −43.65 (80 % −79.15 to −31.85) $MtCO_2e$ in 2070 (Fig. 5A, Table 2), relative to a 'do nothing' baseline. In 2030, rehabilitation increased annual net GHG emission by a median of 0.09 (80 % 0.00 to 0.39) $MtCO_2e\ yr^{-1}$. In 2050, rehabilitation reduced annual net GHG emission by a median of −1.05 (80 % −2.19 to −0.59) $MtCO_2e\ yr^{-1}$ in 2050. The median annual net reduction in 2070 was −3.15 (80 % −4.54 to −1.99) $MtCO_2e\ yr^{-1}$ (Fig. 5B). The median cumulative net mitigation in 2070 was 1.9 % of the cumulative median 2020–70 wildfire emissions for all of BC and 5.7 % of the median cumulative wildfire emissions for the THLB. The median estimated time to achieve cumulative net GHG reduction for all of BC was 26 (80 % 23–31) years, corresponding to the calendar year 2046 (80 % between calendar years 2043 and 2051) (Fig. 5A). Interior sites with low salvage utilization and moderate future stand yield, which were planted to species other than Douglas-fir had the highest net cumulative mitigation benefit in 2070 (-26 [80 % −15 to- 52] $MtCO_2e$ [Table 2]), largely because the rehabilitated area was highest (1122 [80 % 773 to 1704) kha, Table 2) because area burned in the interior is high. Rehabilitation of this stand type yields a relatively modest benefit per unit area of 23 $tCO_2e\ ha^{-1}$, relative to sites on the coast planted with similar species following high utilization salvage harvest, which yield a benefit of 153 $tCO_2e\ ha^{-1}$ rehabilitated (Table 2). However, the total area of rehabilitation in this stand type was only 15 (80 % 8 to 29) kha (Table 2) because area burned in the coast is low. Flux timeseries for each of the regions is provided in the Supplementary Material.

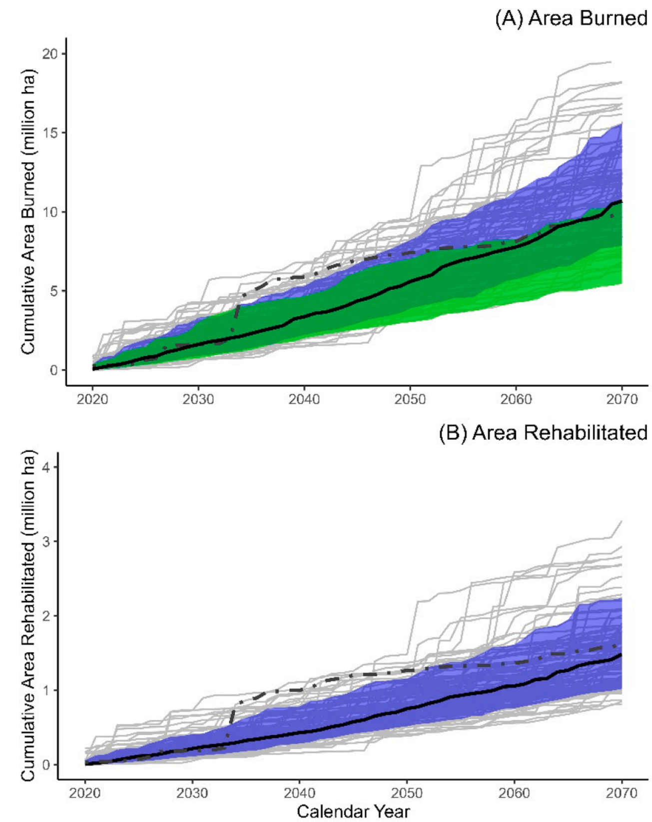

Fig. 3. Cumulative area burned available for rehabilitation (A) and the cumulative area actually rehabilitated (B) in British Columbia, Canada (2020–70). The y-axis in (B) spans 0–4 million ha, 20 % of the 0–20 million ha span in (A). Panels (A) and (B) show the median (black line), 80 % interval (blue ribbon), and each simulation (n = 100, grey lines) under a future fire scenario where area burned doubles over time. Panel (A) also shows the 80 % interval (green ribbon) if area burned did not double over time. The dash-dot line in each panel shows the cumulative area burned (A) and cumulative area rehabilitated (B) in the draw with the 5th highest net cumulative climate mitigation potential. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4. Evaluation of fire history and forecasts

The estimated 100-year area burned in 2021 was 1.66 million ha and the estimated 1 million ha return period was 45 years (Fig. 6). As each year of additional observations is accrued from 1980 to 2021, the estimated 100-year area burned was as high as 1.76 million ha (1982) and

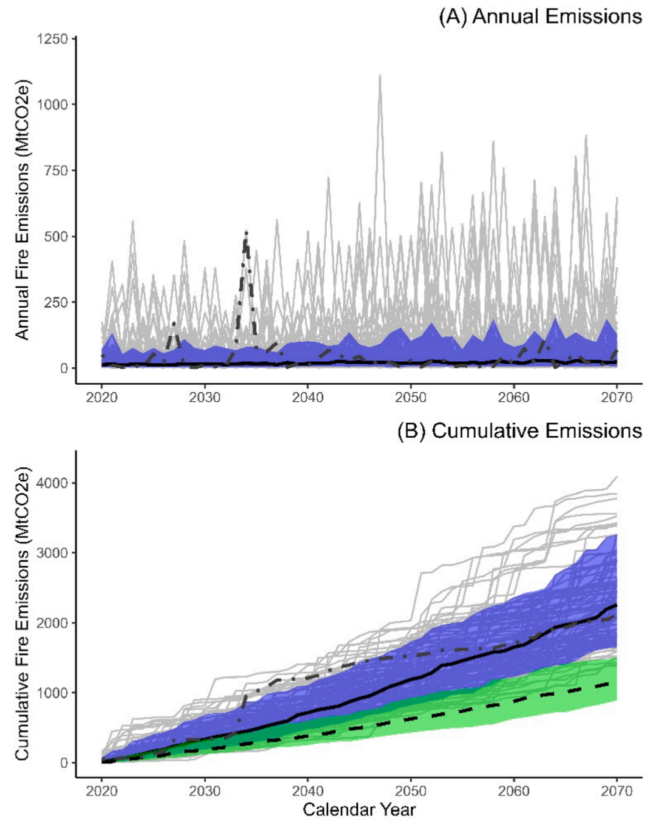

Fig. 4. Annual (Panel A) and cumulative (Panel B) wildfire emissions (2020–70) in British Columbia, Canada, for the REHAB scenario. The median (solid black line), the 80 % interval (blue ribbon), and each simulation under a future fire scenario where area burned doubles over time (n = 100, grey lines) are shown. For reference, Panel B also shows the median (dashed black line) and 80 % interval (green ribbon) from Metsaranta et al. (2011, M11). The dash-dot line in each panel shows the annual (A) and cumulative (B) wildfire emissions in the draw with the 5th highest net cumulative climate mitigation potential. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

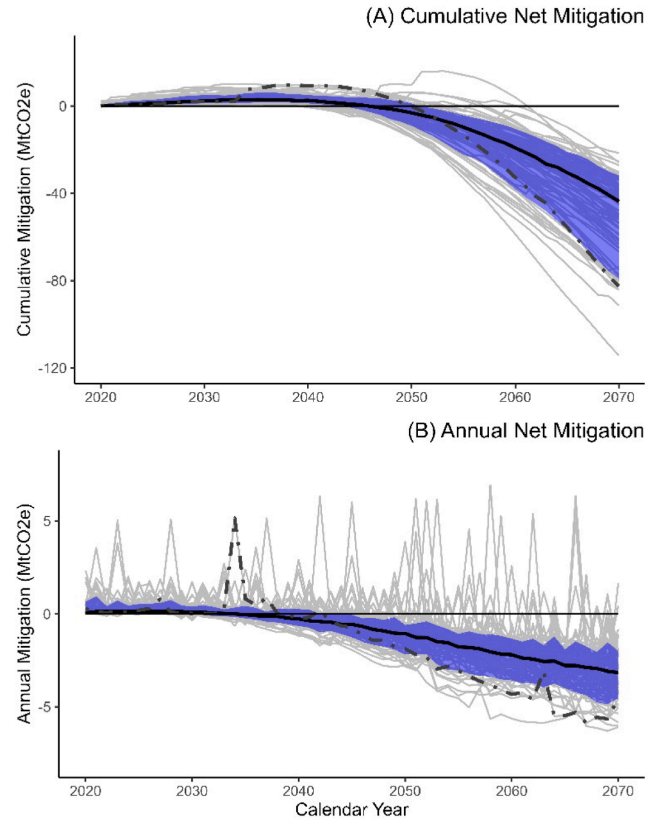

Fig. 5. Cumulative (A) and annual (B) net mitigation potential of post-wildfire rehabilitation in British Columbia, Canada, 2020–70, determined by the difference between each simulation in the REHAB and BASE scenarios. Net mitigation is the sum of contributions from forest, harvested wood products, product substitution and energy displacement. The median (solid black line), the 80 % interval (blue ribbon), and each simulation under a future fire scenario where area burned doubles over time (n = 100, grey lines) are shown. Negative values (below the solid horizontal line at zero) are a climate mitigation benefit. The dash-dot line in each panel shows the cumulative (A) and annual (B) mitigation potential for the draw with the 5th highest net cumulative climate mitigation potential. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

as low as 1.03 million ha (2002) (Fig. 6A). The 1 million ha return period, which is inversely related to the 100-year area burned, ranged from a low of 41 (1982) to a high of 96 (2002) years (Fig. 6B). Point estimates for both statistics varied over time, but only on a few occasions did the annual estimate for either statistic fall outside of the 80 % bootstrap interval in other years (e.g. the point estimate of 100-year area burned in 2021 is above the upper confidence bound for a few of the years between 2002 and 2014, Fig. 6A). The width of the 80 % interval generally decreases with time, particularly for the 1 million ha return period after 2017, when more than 1 million ha burned for the first time. The width of the 80 % bootstrap interval for the 1 million ha return period was reduced to anywhere from one half to one third the pre-2017 width (Fig. 6B).

Any 100-year area burned between 1.82 and 2.02 million ha or 1 million ha return periods between 34 and 38 years in 2070 could have been generated by any of the three future scenarios, observed mean, step doubled mean, or gradually doubled mean, on the basis of the 80 % interval (Fig. 7A and 7B). The overlapping values for the 95 % interval have a greater range: between 1.62 and 2.28 million ha and 30 to 44 years (Fig. 7A and 7B). For the step doubled mean, the most severe future fire scenario, 80 % of the 100 year area burned estimates were between 1.82 and 3.03 million ha (Fig. 7A) and 80 % of the estimates for the 1 million ha return period were between 21 and 38 years (Fig. 7B). The actual 2017–21 area burned was exceeded in only a very small percentage of the observed mean scenarios (2.5 % of n = 10,000 simulated 5 year times series) but was exceeded 10.1 % in the step doubled mean scenarios. Of these simulated 5 year scenarios, 10.9 % (observed mean) and 26.8 % (step doubled mean) had at least one year that exceeded 1 million ha.

4. Discussion

4.1. Rehabilitation

Rehabilitating about 14 % of forests after wildfire in BC over the period 2020–70 achieved a net climate mitigation benefit, relative to a baseline where these activities do not occur. However, these benefits are only realized in the future (between 2043 and 2051 in 80 % of simulations), and the cumulative benefit in 2070 is small (median ~ 2 %) relative to the cumulative amount of direct GHG emissions from wildfire forecast to occur from 2020 to 70 under a scenario where annual area burned increases over time. The analysis considered carbon stored in the whole ecosystem (aboveground biomass, belowground biomass, deadwood, litter, and soil), carbon stored in forest products, and substitution effects. The activities required to rehabilitate stands, salvage harvest that generates wood products and bioenergy, create additional emissions that are initially partially offset by substitution benefits from avoided products, avoided fossil fuel burning, and over time will be

Table 2
Net cumulative GHG emissions ($MtCO_2e$,[median, 80 % range]) by region, parameter group and year. Salvage utilization rate of 75 % occurs when Douglas-fir is salvage harvested. Years to GHG reduction indicate the time required for the cumulative emissions to become a net reduction. Negative values indicate a reduction in emissions relative to a 'do nothing' baseline.

Region	Harvest Utilization Rate (%)	Replanted Yield	Net cumulative GHG ($MtCO_2e$)			Years to GHG reduction	Cumulative Area Rehabilitated in 2070 (kha)
			2030	2050	2070		
Coast	75	High[a]	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	−0.0 (−0.0, 0.0)	37 (18, NA)	0.0 (0.0, 0.0)
		Moderate	0.1 (0, 0.4)	−0.2 (−0.7, 0)	−2.3 (−4.2, −1.2)	25 (19, 30)	15 (8, 29)
	50	High	0.3 (0.1, 0.7)	−0.3 (−1, 0.2)	−3.5 (−5.6, −2.2)	27 (21, 32)	39 (26, 61)
		Moderate	0.3 (0.1, 0.7)	0 (−0.5, 0.5)	−2.8 (−4.2, −1.8)	31 (24, 38)	48 (35, 76)
Interior	75	High[b]	nil	nil	nil	nil	nil
		Moderate	1.8 (0.6, 4.8)	1.7 (0.1, 6.1)	−7.8 (−17.3, −3.8)	36 (31, 43)	176 (97, 388)
	50	High	0.6 (0.3, 1.2)	0.5 (0.2, 1.1)	−3.1 (−5.5, −1.5)	36 (32, 41)	64 (43, 99)
		Moderate	6.1 (3.3, 11.7)	6.7 (2.7, 13.7)	−26 (−52, −15)	37 (33, 44)	1122 (773, 1704)
BC	All	All	2.4 (1.2, 5.0)	−3.1 (−9.0, 1.2)	−43.6 (−79.2, −31.9)	26 (23, 31)	1486 (1020, 2237)

[a] A small amount of activity occurs in this category, but it is below the rounding level.
[b] No events in this category occurred in the simulations, so the impacts could not be assessed.

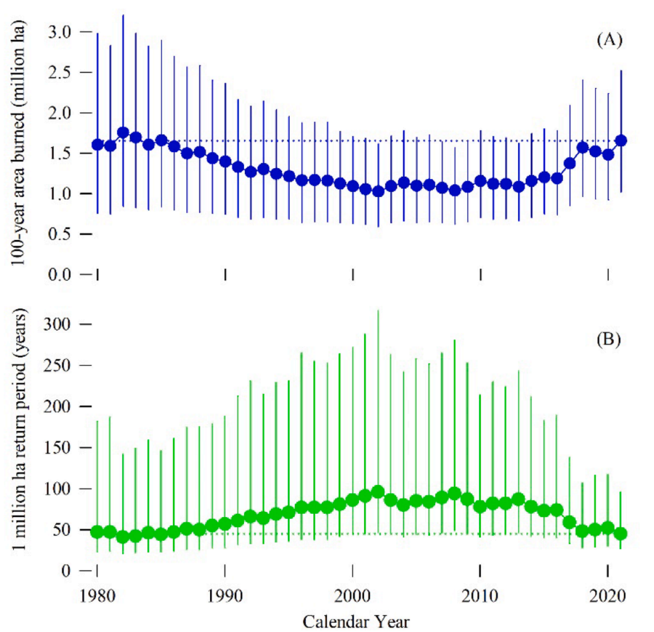

Fig. 6. Estimates of the 1 million ha return period (years) (A) and the 100-year return period (million ha) (B) in British Columbia, Canada, as each year of annual area burned statistics after 1980 is added to the observational time series that begins in 1950. The 2019–2021 data were not used in the C forecasts. Error bars are 80 % intervals from n = 10,000 bootstrap simulations. The horizontal dashed line highlights the 2021 estimate.

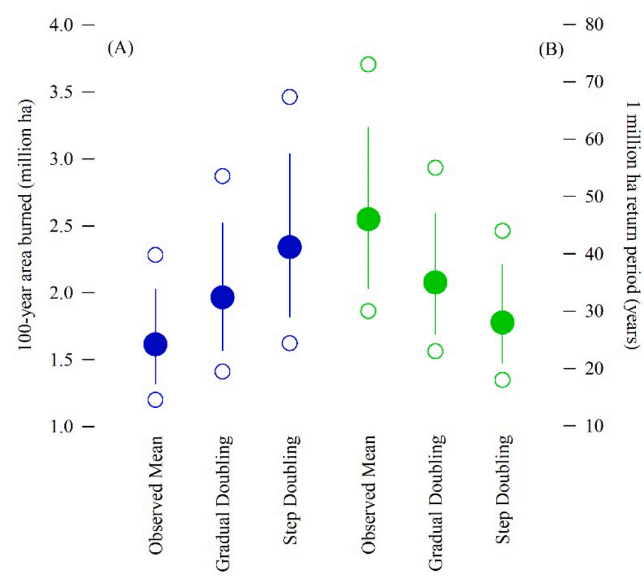

Fig. 7. Possible estimates of the 100-year area burned (million ha) (A) and the 1 million ha return period (years) (B) that could be observed in 2070 under three annual area burned scenarios in British Columbia, (1) 1950–2021 observed mean, (2) a mean that gradually doubles from 2022 to 2070, and (3) a mean that step doubles in 2022. The filled circle is the median, the errors bars the 80 % interval, and the outer circles the 95 % interval from n = 10,000 Monte Carlo simulations of each scenario.

completely offset by higher productivity in rehabilitated stands relative to natural stands. Conversion to managed yield curves made the greatest contribution to enhanced mitigation, even though we made relatively conservative assumptions about managed yield (greater early growth but not necessarily a higher maximum stand capacity to store C). In this study we focused on projecting future wildfires, assessing rehabilitation areas and modeling the GHG benefit of salvage harvest and regrowth. Additional activities could be examined including activities to reduce wildfire severity, using salvage harvest in place of clearcut harvest (Smyth et al., 2014), greater use of harvested wood for longer-lived products with high substitution benefits (Xie et al., 2021), and collection of harvest residues for bioenergy and/or biofuels (Howard, 2020; Smyth et al., 2020). We also made conservative assumptions that salvage harvest utilization rates are lower than standard clearcut utilization rates, based on fibre quality, but did not consider specific impacts on fibre quality such as the timing of the fire, fire temperature, or time window for salvage operations (Barrette et al., 2013; Mansuy et al., 2015). Haul costs and salvage biomass for bioenergy and biofuels are considered in a companion paper (Smyth et al., in review).

The timing and magnitude of mitigation benefits after rehabilitation varied as function of region, harvest utilization rate, and rehabilitated stand yield (Table 2). The initial emissions debt caused by rehabilitation is greatest where more post-harvest residues are burned in situ to abate wildfire risk, and where post-fire wood quality was assumed to have low salvage utilization rates, leaving behind more harvest residues. Lower utilization rates also impact transfers to HWPs and therefore potential substitution benefits. The net GHG benefit per ha is greater for the coast, for higher salvage utilization rates, and when post rehabilitation stand yield is high relative to baseline yield when the stand is not rehabilitated. However, most of the rehabilitated area in this study is in the interior region because that is where area burned is highest Interior stands were assumed to need more fuel reduction, to have a lower salvage harvest utilization rate and to have a smaller increase in post rehabilitation growth rate relative to the no rehabilitation baseline than coastal stands. The mitigation benefit in this study relies mainly on contributions from forest regrowth that come many years after stands are salvage harvested and planted, putting critical importance on the survival of rehabilitated sites when considering investing in this form of GHG mitigation. Generally, contributions to annual mitigation in a given year are greatest from areas rehabilitated approximately 30–40 years prior due to the time required for C uptake from newly planted stands to become significant and exceed that of the non-rehabilitated stands. Relatively few rehabilitated stands re-burned during the simulations because the area treated was small, fires were distributed randomly in the landscape, and forest younger than 10 years were assumed to not burn. This may be underestimating the risk of failure because fire risk varies spatially, and other possible causes of failure, such as insect or drought, were not considered. Similarly, the assumptions for the baseline scenario also did not address risks of failure of forest regrowth after wildfire.

The analysis focused on central statistical tendencies of each indicator of interest. No individual simulation precisely follows the smooth time course suggested by the statistical central tendency, nor will reality follow such a course from the present to 2070. Figs. 2 through 5 also highlight the time series of estimated values for the single simulation with the 5th highest net cumulative mitigation, where a relatively high area burned year occurred early, in 2034, when 2.6 million ha burned (Fig. 3A, Fig. 4A). To achieve this mitigation benefit in practice would require a combination of chance and preparation. Because it takes in the order of 30–40 years after rehabilitation to accrue mitigation benefits, the 0.57 million ha rehabilitated (Fig. 3B) in response to this event had time to achieve benefits before 2070. This is the chance part of the equation. In this particular simulation, the area annually rehabilitated ranged from 153 ha to 580 kha, which varies widely from the median area annual rehabilitated (~12 kha) across all draws and years. In reality operational constraints will make it impossible to salvage harvest and rehabilitate an area 2 to 3 times the annual harvest area[9]. To take any advantage of post-fire rehabilitation would require building and maintaining capacity to respond in some way to unpredictable opportunities, and the cost of this would have to be weighed against benefits of alternative investments such as fire preparedness. Moreover, in reality increased salvage logging after high fire years would be accompanied by a reduction in green tree harvest elsewhere in the province. This shift in harvest allocation from green tree to salvage harvest will increase the mitigation benefits because delaying harvest of green trees will in most cases allow the unharvested stand to accumulate more carbon (e.g., Smyth et al., 2014, Drever et al., 2021) while transferring to the product sector C from fire-killed trees in burned stands that will decompose or is at risk from future fires.

4.2. Evaluation of future fire risk

It is very likely that climate warming has already increased area burned in BC (Kirchmeier-Young et al., 2019), and the difference between the 1950–2005 and 1950–2018 observed mean return period curves in Fig. 2, as well as the differences in the log normal mean annual area burned in Table 1, corroborate this conclusion. In the C forecasts, we assumed that mean area burned would double in the future, beyond the 1950–2018 observed mean. We wished to consider if the assumption that area burned would continue to double is realistic because both the log normal mean annual area burned (Table 1) and the estimated return period curve (Fig. 2) for the 1950–2005 doubled mean scenario and the 1950–2018 observed mean scenario are similar. A possible interpretation of this observation is that mean annual area burned has already doubled and is therefore already reflected in the projections based on the 1950–2018 observed mean. A corollary of this interpretation is that a further doubling beyond this, as assumed in the C forecasts, would overestimate future risk.

While there is strong evidence to suggest that wildfire risk will on average continue to increase, there will continue to be highly stochastic inter-annual variation in area burned in the future, just as there has been in the past (Armstrong 1999, Metsaranta 2010). Return period analysis in hydrology assumes that the probability distributions for describing event magnitudes will stabilize over a long period of observations unless underlying conditions change (Rao and Hamed, 2000), and climate change has invalidated this assumption (Milly et al., 2008). Similarly, large inter-annual variation causes instability in statistical characterizations of area burned (Armstrong, 1999), and observed area burned may be consistent with different underlying risk levels (Metsaranta, 2010). Post-1980 variation in the estimated values for both the 100-year area burned and the 1 million ha return period suggest that estimates for extreme events have been both unstable and uncertain in the past (Fig. 6). Point estimates of the 100-year area burned and 1 million ha return period after 2021 are similar to estimates that would have been calculated in the early 1980 s, but with lower uncertainty (Fig. 6).

There is a large amount of evidence to suggest that wildfire risk has increased and will continue to increase in BC (e.g. Kirchmeier-Young et al., 2019), and the extreme annual area burned in 2017–2021 corroborates this conclusion. Three of 5 years had large area burned, and no five year period in the available record approaches the 2017–21 total. If we assume that our method of estimating future annual area burned as a highly variable stochastic process is reasonable, then regression to the mean suggests that the most likely short-term outcome is that area burned in the near future will be lower. This is borne out in our short-term projections, where even the most pessimistic assumption (step doubling of the mean annual area burned) suggest that there is a 9 in 10 chance that total area burned from 2022 to 26 will be less than the 2017–21 total. At the same time, however, there is also a non-trivial chance, about 1 in 4 under the step doubling scenario, that at least one of the five years 2022–26 will be larger than 1 million ha. It is important to also note that long periods of low area burned have also occurred. The lowest 100-year area burned and longest 1 million ha return period post-1980 (Fig. 6) followed 17 years (1986–2002) of very low area burned (Fig. 2A), with maximum 0.08 and cumulative total 0.41 million ha area burned, ~20 % of the 2017–18 total. The frequency of both 17 successive years < 0.08 and 2 successive years greater than 1 million ha is about 2–3 % based on 10,000 69-year series simulated from the 1950–2018 observed mean parameters (Table 1). This suggests that both the 17 year low period from 1986 to 2002 and the 2 year high period in 2017–18 were both equally rare events under past climate conditions.

The probability of extreme events has most likely increased, due to factors including higher fuel load, longer fire seasons, increased drought, and more frequent lightning (Aftergood and Flannigan, 2022). However, an increase in the probability and size of rare events does not guarantee their occurrence, and periods of low area burned will also occur between now and 207 0. This is not merely of academic concern because a non-trivial proportion of long-term future estimates of the 100-year area burned or the 1 million ha return period generated by the step or gradually doubled mean future distribution does not reflect the actual increase in underlying risk conditions because by random chance they are also consistent with a future where area burned has not

[9] https://nfdp.ccfm.org/en/data/harvest.php.

continued to double beyond the recent mean (Fig. 7A and 7B). In the worst case this could be misinterpreted as a lack of change in the underlying risk conditions, a conclusion that should be avoided. Under the most severe future scenario, step doubling in 2022, the upper bounds of the estimated 100-year area burned could be from 3.03 to 3.46 million ha (90th and 97.5th percentile, respectively). For the 1 million ha return period, the lower bound could be from 21 to 18 years (10th and 2.5th percentile, respectively). While it is now better understood that years where more than 1 million ha burned are possible, there is also less certainty about just how large extreme events could be. It is very likely that future annual area burned will exceed both 1 million ha one or more times between the present and 2070. Annual area burned greater than 2.0 million ha are possible, regardless of whether average area burned continues to double beyond the 1950–2018 or 2021 observed mean or not (Fig. 7A). If average area burned does indeed double beyond this observed mean, then even 3 million ha is a possibility. Such predictions are of course extrapolations, and should they occur, could influence landscape characteristics (less fuel) to a degree that subsequent area burned could be reduced.

4.3. Additional considerations

Climate change will influence more than just future annual area burned. For example, fire severity is also an important factor influencing carbon emissions (Conard et al. 2002) that may increase in the future. Fire severity is not currently classified for historical burned areas in British Columbia. Remote sensing products classifying fire severity in Canada since 1985 have recently become available (Guindon et al. 2021) and research continues to translate estimates of fire severity into mortality and emissions estimates. A useful follow up study could compare the resulting emission estimates to independent data such as the global fire emissions database (GFED; Giglio et al. 2013, Van Der Werf et al. 2017) for model validation. This information will be very useful in future efforts to forecast changes in fire severity. High frequency and severity fire will increase carbon emissions, but it also creates charcoal that can store carbon for a long period (Wei et al., 2018), an additional factor that could be considered. It is also known that tree growth in British Columbia will also be affected by climate change (Hember et al. 2012; Hember et al. 2018). Growth rates were only altered in the REHAB scenario, and only for sites that received the rehabilitation treatment, by using managed yield tables in place of natural yield tables. However, climate does not currently affect future growth rates in either of the forest management growth models (TASS-TIPSY, VDYP7) used to derive the yield tables. Regional and national approaches for incorporating climate sensitivity into growth predictions from forest management models are ongoing.

5. Conclusions

We evaluated post-wildfire rehabilitation as a forest management activity to increase C sequestration in BC's forest and found that a cumulative net GHG benefit relative to a 'do nothing' approach would occur in about two to three decades and would increase in time. We also identified that the mitigation benefit would be higher with high salvage harvest utilization rates, less burning of harvest residues, and faster rates of regrowth in rehabilitated stands, all conditional on the rehabilitated sites not burning in subsequent wildfires. To arrive at these conclusions, the analysis considered carbon stored in the whole ecosystem (aboveground biomass, belowground biomass, deadwood, litter, and soil), carbon stored in forest products, and substitution effects. In future work, the estimated benefits of rehabilitation could be improved by better constraining these assumption to match on the ground operational conditions, for example, implementing more reasonable regeneration delays in the baseline, adjusting to planted species to match alternative management options (for example, bioenergy, fire tolerance, or climatic sensitivity) and, most importantly, reducing green tree harvest following years with high fires when salvage harvest will provide a larger proportion of the timber required by society. However, under the current assumptions, overall mitigation benefit of rehabilitation was small (median ~ 2 %) relative to the cumulative emissions from future wildfires. The simple approach used to forecast future area burned in this study (Armstrong 1999; Metsaranta 2010) generates widely variable projections, and future work will examine how more complex fire risk models that take into consideration how changes in landscape characteristics with different fire and management regimes might affect the conclusions. One way in which the results could differ is by accounting for spatial variation in the probability of burning (Wang et al., 2016), a key landscape characteristic that it may be possible to modify through mitigation actions. Additional forest management activity to reduce wildfire emissions by reducing ignition probability or flammability, or reducing fuel loads and thus emission per hectare burned could have a stronger influence on emissions reduction than increasing post-fire rehabilitation. Ongoing work[10] is examining forest management activities that can reduce fire severity and assess the feasibility of reducing future wildfire emissions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120729.

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