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Vulnerability of timber supply to projected changes in fire regime in Canada's managed forests

S. Gauthier, P.Y. Bernier, Y. Boulanger, J. Guo, L. Guindon, A. Beaudoin, and D. Boucher

Abstract: The frequency of forest fires is predicted to increase in Canada, which may affect the availability of timber for industrial purposes. We therefore carried out an evaluation of the timber supply vulnerability to current and future fire risk through simplified calculations involving historical forest growth and harvest rates and current and projected forest burn rates. Calculations were performed at the level of forest management areas (FMAs) across the boreal and montane ecozones of Canada. For some FMAs, the vulnerability of timber supply to fire was estimated to be high to extreme by the middle of the century. For those FMAs, the increases in tree growth necessary to negate these risks were generally unrealistic. A modest simulated decrease in tree growth over time, however, was sufficient to raise the vulnerability of many other FMAs from low to moderate. Known biases in the analysis suggest that our assessment might underestimate the level of vulnerability in all FMAs. Other natural disturbances are not included in the analysis but their impact on timber supply may be additive to that of fire. Some adaptation measures to face these increasing risks are discussed.

Key words: boreal forest, productive capacity, fire risk, climate change, vulnerability.

Résumé : Les prédictions courantes suggèrent une augmentation de la fréquence des feux au Canada, ce qui pourrait affecter la disponibilité en bois pour des fins industrielles. Nous avons donc évalué la vulnérabilité de l'approvisionnement en bois au risque de feux actuel et futur grâce à des calculs simplifiés impliquant les taux de récolte et la croissance historiques de la forêt, ainsi que les régimes de feux actuels et projetés. Les calculs ont été effectués au niveau des unités d'aménagement forestier (UAF) compris dans les écozones boréales et montagnardes du Canada. Pour certaines UAF, l'analyse suggère une vulnérabilité élevée à extrême de l'approvisionnement en bois au feu d'ici le milieu du siècle. Pour ces UAF, les augmentations de croissance des arbres nécessaires à atténuer ces risques sont généralement irréalistes. Une diminution modeste de la croissance de l'arbre au fil du tempsserait cependant suffisante pour augmenter de faible à modérée la vulnérabilité dans toutes les UAF. Des biais connus dans l'analyse suggèrent que notre évaluation pourrait sous-estimer le niveau de vulnérabilité dans toutes les UAF. Les autres perturbations naturelles ne sont pas incluses dans l'analyse, mais leurs impacts sur l'approvisionnement en bois pourrait ent être additifs à celui du feu. Certaines mesures d'adaptation pour faire face à ces risques croissants sont présentées.

Mots-clés : forêt boréale, capacité productive, risque de feu, changement climatique, vulnérabilité.

Introduction

Forest fire is a major disturbance that can compete with harvesting or other forest uses in many parts of the world, notably in boreal and Mediterranean biomes (Marlon et al. 2008; van der Werf et al. 2010). Forest fires burn, on average, about 2 Mha of Canada's forests every year (Stocks et al. 2003; National Forestry Database, http://nfdp.ccfm.org), mostly in the northern and continental regions. Such large-scale natural disturbances are part of the normal dynamics that shape these forest landscapes (Johnson 1992). Regionally, their risk of occurrence increases with increased climate dryness (Flannigan et al. 2005) and importance of boreal conifers in the landscape (Girardin et al. 2013). Recently, Boulanger et al. (2014) delineated zones of homogeneous fire regimes (HFR) across Canada based on long-term fire statistics, among which the historical (1959–1999) annual burn rate varies from 0.03%-year⁻¹ to 1.48%-year⁻¹.

Strategic forest management planning in these mostly northern forests includes projections of constant harvest rates over long time frames, typically 100 to 150 years, to assess their sustainability with respect to desired environmental and structural properties of the forest landscape. Such long time frames are significant as they now encompass large projected changes in climate for high-latitude regions (Collins et al. 2013). Throughout the planning period, forest fires compete with forest management by burning forest stands that would have been harvested in the future and by shifting the age structure of forest landscapes to younger age classes, thus affecting the availability of future mature timber for harvest (Boychuk and Martell 1996). Their random nature both in time and space makes them difficult to incorporate into the forest management planning of individual forest management areas (FMAs) within which forest companies operate. As a result, fires create periodic shortfalls in timber supply, meaning that within a given FMA where a fire has occurred and for a given number of years, the amount of wood available for harvest will be lower than the previously planned long-term harvest rate (Leduc et al. 2015).

Past fire regimes have been shown to fluctuate as a function of changes in climatic conditions (e.g., Ali et al. 2012). Similarly, ongoing and projected changes in climate across Canada's forests may lead to drier and warmer conditions with concomitant increases in the area burned across Canada's fire-prone forest land-scapes (Flannigan et al. 2005; Boulanger et al. 2014). Future increases in burn rates may therefore have an increasingly nega-

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tive impact on the availability of timber for industrial use, and the identification of where such vulnerabilities may occur is an important step towards the adoption and implementation of adaptation measures (Gauthier et al. 2014). The objective of this work was therefore to evaluate the vulnerability of timber supply to future fire activity across the boreal and montane forest ecozones of Canada's managed forests. Specifically, we wanted to know where, when, and to what extent current harvest regimes within FMAs across Canada would be at risk of creating timber shortfalls due to projected increases in burn rates.

The analyses were carried out and are reported at the level of FMAs. Although the limits of these areas change over time as a function of provincial administrative decisions, they represent land units of regionally relevant size and distribution for the planning and deployment of forest management activities. In addition, the computations are theoretical as they do not incorporate all local constraints on forest operations. The results therefore do not present accurate evaluations of timber shortfalls, but rather identify areas of vulnerability to such outcomes. In the current exercise, we define timber supply as the area harvested by FMAs for the 2001 to 2010 period, as determined using the large forest disturbance product of Guindon et al. (2014) described below. Biases and uncertainties associated with the computations are covered in the Discussion section.

Material and methods

Study area

The study area encompassed the managed forest within the five boreal and montane ecozones of Canada (taiga plains, boreal cordillera, boreal plains, boreal shield, and montane cordillera; Ecological Stratification Working Group 1996). Much of the land base of these ecozones is in public ownership and currently under some form of timber license. As mentioned earlier, large fires are common across these vast landscapes. Other natural disturbances such as insect outbreaks and drought also affect forest mortality and growth across these regions but were not considered in this analysis. The boundaries of the five ecozones of interest were intersected with Canada-wide outlines of FMAs for 2004 (www. databasin.org), and the forest area within the FMAs within these ecozones (125.6 Mha) was retained for further analysis. These FMAs of interest are simply referred to as "FMA" in the following text.

In addition to the FMA outlines mentioned above, the information to be used in our analysis was extracted from three specific Canada-wide spatial datasets. (1) Forest properties (e.g., volume, age, composition) were obtained from the maps generated by Beaudoin et al. (2014) that provide full coverage of Canada's forests at a pixel resolution of 250 m × 250 m (6.25 ha). This set of maps was created for base year 2001 using the nonparametric k-nearest-neighbour as the statistical estimation method, the National Forest Inventory photoplot data (Gillis et al. 2005) as reference information, and a set of Canada-wide variables including MODIS spectral reflectance at 250 m × 250 m (6.25 ha) pixel resolution as predictors. (2) Historical (2001-2010) harvest rates were obtained for each FMA using the yearly large disturbance maps generated by Guindon et al. (2014) using MODIS spectral reflectance to identify, for each year, the 250 m × 250 m (6.25 ha) pixels in which forest harvest had taken place and the fraction actually harvested within each of these pixels. (3) Annual burn rates were obtained from the homogeneous fire regime maps prepared by Boulanger et al. (2014) for historical (1961-1990) and projected (2011-2040, 2041-2070, 2071-2100) periods. However, for the current analysis, projections were recalculated using the equations

derived by Boulanger et al. (2014) but computed with the climate projections of the representative concentration pathways (RCP) instead of the SRES projections used originally. Details of the computation of annual burn rates are described in Supplementary Material S1¹.

The overall analysis entailed expressing the yearly constant harvest rate by FMA as a fraction of a theoretical harvest rate that was calculated to represent the maximum potential area-based harvest for that FMA, without and with accounting for fire risk. The analysis also assumed that forest composition and growth rates were time invariant. The flow of the analysis is described in Fig. 1 and entailed both pixel-level and FMA-level computations.

Calculating the theoretical harvest rate without fire (H_T)

The first step in the analysis was to evaluate a FMA-level theoretical harvest rate without fire (H_T) as a function of the FMA mean tree growth rate and with a forest age structure that was assumed to be fully regulated (i.e., with a constant area per stand age class). To estimate this mean growth rate, we developed pixel-level yield curves of gross merchantable volumes (V, m³·ha⁻¹) as a function of age (A) for two aggregated species groups (coniferous and deciduous) across Canada's managed forests using a formulation modified from that used by Ung et al. (2009):

(1)
$$\log(V) = \beta_0 + \beta_1 T + \beta_2 P + \frac{\beta_3 + \beta_4 \text{Temp} + \beta_5 P}{A}$$

where Temp is historical (1970–2000) mean annual air temperature (°C), *P* is historical mean annual precipitation (mm), and β_0 to β_5 are parameters to be adjusted. The conversion from logarithmic units to arithmetic units entailed the use of a correction factor, as suggested by Duan (1983) (in Ung et al. 2009):

(2)
$$V = \exp[\log(V)] \times C_{\Gamma}$$

where $C_{\rm D}$, the Duan correction factor, is equal to the mean of exponentiated residuals.

The yield eqs. 1 and 2 were parameterized using data drawn from a Canada-wide set of 30 090 forest pixels created by rasterizing forest polygons provided by provincial forest agencies to Canada's National Forest Inventory (NFI) as part of the 1% Canada coverage of the NFI photoplot product (Gillis et al. 2005). These pixels were created and used by Beaudoin et al. (2014) as a reference for generating their Canada-wide forest properties maps. To parameterize the coniferous and deciduous yield curves, we retained from this dataset only the pixels in which forest composition was either at least 75% coniferous or at least 75% deciduous and expressed their merchantable volume per hectare of vegetated area within each pixel. The adjustment was carried out using the "ROBUSTREG" procedure of the SAS software package (SAS 9.3; SAS Institute Inc., Cary, North Carolina) within which outliers were detected and deleted. In total, 13 856 pixels were retained for model adjustment. It should be noted that the 2001 forest properties layers of Beaudoin et al. (2014) slightly predate a severe decade-long insect outbreak in central British Columbia (Taylor et al. 2006). All values calculated for this montane region therefore reflect the pre-epidemic state and productivity of the forest cover.

Following their parameterization with the "reference" pixels, the two yield equations were then applied to all forest pixels within each FMA. These pixels were first identified by intersecting the FMA boundaries with the forest properties maps of Beaudoin

¹Supplementary material is available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2015-0079. See cjfr-2015-0079suppla.pdf for Supplementary Material S1–S5 and cjfr-2015-0079supplb.pdf for Supplementary Material S6 (maps).

Fig. 1. Information flow from the four databases (shaded boxes: forest properties (Beaudoin et al. 2014), fire regime (Boulanger et al. 2014), forest harvesting (Guindon et al. 2014), and FMA polygon boundaries (www.databasin.org)), through the various equations (ellipses), to the generation of variables (open boxes). Abbreviations of variables are as follows: A_{Mi} , age to commercial maturity; F_{Ri} , fire risk; H, observed yearly harvest rate; H_T and H_{TF} , theoretical yearly harvest rate without and with fire, respectively; and H_R and H_{RF} , relative harvest rate without and with fire, respectively. Note that the parameterization and application of eqs. 1 and 2 were done using two different sets of pixels, both extracted from the forests properties datasets of Beaudoin et al (2014).



et al. (2014). From this intersection, we extracted by FMA for each forest pixel the values of V (m³ per total pixel area), A (years), species group (% forest cover by coniferous and deciduous species), within-pixel fraction of vegetated area, and values of T and P that were used as predictors by Beaudoin et al. (2014). The value of V for each pixel was rescaled to express the volume V per hectare of within-pixel vegetated area. For the remainder of the text, we refer to values of A and V thus extracted from the forest properties maps as "measured", whereas values of V calculated from eqs. 1 and 2 are referred to as "modeled".

Within each FMA, each pixel was then assigned a single realization of eqs. 1 and 2 based on the pixel-specific values of *T* and *P* for each of its two species groups as parameterized above. The resulting two curves were merged into a single composite pixel-level yield curve using the within-pixel relative abundance of coniferous and deciduous species. For each individual pixel, the composite yield curve was then multiplied by a scaling factor equal to the ratio of measured to modeled *V* at the measured age *A* to force the curves to locally adjust to the observations.

We then used the scaled, composite pixel-level yield curves to estimate the age at which each pixel reached its commercial maturity ($A_{\rm Mi}$), where commercial maturity was arbitrarily defined as $V = 100 \, {\rm m}^3 \cdot {\rm ha}^{-1}$ for the two species groups combined. Using a single value of commercial maturity across jurisdictional boundaries enabled us to produce a uniform vulnerability assessment across the area of interest. Use of any other arbitrary value would have produced similar results of relative vulnerability in this assessment. Pixels in which $A_{\rm Mi}$ exceeded 200 years were considered unproductive and removed from the dataset. At this point, the productive forest within the FMAs of the five forested ecozones was represented by over 20 million 250 m × 250 m pixels, or about 126 × 10⁶ ha.

As mentioned earlier, we applied the simplifying assumption that the stand age structure within each FMA was that of a fully regulated forest. In such a forest structure, in the absence of natural disturbances, the mean $A_{\rm M}$ across an FMA represents the rotation age, and the value $1/A_{\rm M}$ defines the fraction of the land to be harvested each year (Bettinger et al. 2008). While recognizing that the age-class structure of Canada's natural forests is not that of a regulated forest (see the Discussion section), we applied this

principle to each FMA and calculated the FMA-specific theoretical harvest rate without fire (H_T , fraction-year⁻¹) as

$$H_{\rm T} = \frac{\sum_{i=1}^{n} \frac{1}{A_{\rm Mi}}}{n}$$

where A_{Mi} represents the age to commercial maturity of pixel *i* and *n* is the number of productive pixels in the FMA.

Calculating the relative harvest intensity without fire (H_R)

The second step in the analysis was to evaluate the relative harvest intensity without fire (H_R , fractional; Fig. 1) by FMA as the ratio of the historical yearly harvest rate (H) to the theoretical harvest rate without fire (H_T). The value of H per FMA was estimated as the mean 2001 to 2010 yearly fraction of productive area harvested within that FMA:

(4)
$$H = \frac{\sum_{j=1}^{10} \sum_{i=1}^{n} f_{ij}}{n \times 10}$$

where *n* is the number of productive pixels within a given FMA, f_{ij} is the fraction of productive pixel *i* that was actually harvested in year *j* as per the estimates of Guindon et al. (2014), and 10 accounts for the 10 years of harvest in the dataset. The 2001 to 2010 period was also marked by a sharp decline in harvest rates across Canada (Fig. 2), largely driven by the drop in the US housing market. Therefore, for each FMA, we computed values of *H* for the highest harvest rate year (H_{MAX} in 2004, 625 × 10³ ha), the lowest harvest rate year (H_{MIN} in 2009, 312 × 10³ ha), and a mean period-wide value *H* (498 × 10³ ha). As the FMAs do not cover the full extent of the ecozones, these values are somewhat lower than the ecozone totals of Guindon et al. (2014) (Fig. 2). The FMA-specific relative harvest intensity without fire (H_R) was then computed as the ratio of *H* (or H_{MAX} or H_{MIN}) to H_T . The value of H_R represents the frac-

Fig. 2. Annual area harvested by ecozone and total for the five ecozones considered in this analysis, as estimated using the annual disturbance maps of Guindon et al. (2014), which capture about 70% of all harvested areas.



tion of annual growth that is being harvested without considering the possible depletion by fire.

Calculating the relative harvest intensity with fire (H_{RF})

The third step in the analysis was to incorporate the risk of fire and calculate the relative harvest intensity with fire (H_{RF} , fractional; Fig. 1) as the ratio of the historical yearly harvest rate (H) to the theoretical harvest rate in which the probability of fire has been incorporated (H_{TF}). The risk related to the regional burn rate (F_{Ri}) was defined as the probability that a pixel would burn before reaching age A_{Mi} and was calculated for each pixel as in Raulier et al. (2013):

(5)
$$F_{\mathrm{R}i} = 1 - \exp(-A_{\mathrm{M}i} \times B)$$

where B represents the historical or projected annual burn rate for the region within which this pixel is found, F_{Ri} is expressed as a fraction, and the initial subtraction from 1 transforms the probability of surviving up to the target age, as per Raulier et al. (2013), into the probability of burning before that target age. Regional values of B for historical and projected climate regimes were estimated for each HFR (Boulanger et al, 2014). For this exercise, burn rates B for periods 2011 to 2040 and 2041 to 2070 were projected using the representative concentration pathway (RCP; van Vuuren et al. 2011) 8.5 climate projection for periods 2011 to 2040 and 2041 to 2070, and both RCP4.5 and RCP8.5 from 2071 to 2100, with the burn rates of the two scenarios being distinct only after 2071. Values of F_{Ri} were calculated with eq. 5 using the historical and projected values of B. The theoretical harvest rates that account for fire risk (H_{TE}) for each FMA for the current climate and for the five climate projections were then calculated as

(6)
$$H_{\rm TF} = \frac{\sum_{i=1}^{n} \frac{1 - F_{\rm Ri}}{A_{\rm Mi}}}{n}$$

where all symbols are defined as above (see also Fig. 1). Although eq. 6 is applied at the level of an FMA, the values of fire risk F_{Ri} are pixel-specific because a given FMA can intersect two or more HFR zones. Note also that H_{TF} corresponds to H_{T} from which we subtract the probability of burning before reaching age A_{Mi} (see eq. 3).

The relative harvest intensity with fire by FMA ($H_{\rm RF}$) was then computed as the ratio of H to $H_{\rm TF}$. Values of $H_{\rm RF}$ were also calculated using maximum and minimum yearly harvest rates ($H_{\rm MAX}$ and $H_{\rm MIN}$).

In theory, a value of $H_{\rm R}$ or $H_{\rm RF}$ below 1 for an FMA indicates a current harvest rate lower than the theoretical harvest rate and, therefore, a low probability of periodic timber shortfall. In practice, however, uncertainties and assumptions in our exercise make such a threshold more approximate. We therefore classified the $H_{\rm R}$ or $H_{\rm RF}$ results into four bins of FMA-level timber supply vulnerability for final representation: $0 < H_{\rm RF} \leq 0.75$ for low vulnerability, $0.75 < H_{\rm RF} \leq 1.25$ for moderate vulnerability, $1.25 < H_{\rm RF} \leq 2$ for high vulnerability, and $H_{\rm RF} > 2$ for extreme vulnerability. In this manner, we emphasize the relative rating among FMAs rather than the underlying numerical value.

Investigating the effect of changing growth rates

Climate change will likely affect tree growth, but the yield eq. 1, although containing climate variables, was not designed to be used to project tree growth with climate change, as discussed by Ung et al. (2009). Instead, as a final step, we calculated the change in forest growth that would be required within each FMA to raise or lower the value of $H_{\rm RF}$ to 0.75, a value representing the threshold separating low from moderate vulnerability. This meant raising growth for FMAs with moderate to extreme vulnerability $(H_{RF} \ge 0.75)$ and lowering it for FMAs with low vulnerability ($H_{\rm RF}$ < 0.75). This analysis was implemented by uniformly multiplying the age to commercial maturity A_{M} of all productive pixels within an FMA by a gradually decreasing or increasing modifier centered on 1 until its FMA-level $H_{\rm RF}$ became equal to 0.75. At that point, the inverse of this modifier gave the proportional change in growth that would be required to reach the threshold between low and moderate vulnerability.

Results

Yield eqs. 1 and 2 were successfully adjusted to the reference pixel database, giving coefficients of determinations of 0.41 and 0.37 for the coniferous and deciduous species groups, respectively (Table 1; Supplementary Material S2¹). The application of these yield equations to pixels within FMA enabled us to estimate an age at commercial maturity (A_{Mi}) and thus eliminate unproductive pixels ($A_{Mi} > 200$). Overall, the proportion of productive pixels

Table 1. Fit statistics and parameter values for eqs. 1 and 2 for the coniferous and deciduous aggregated species groups.

	Coniferous		Deciduous	
	Estimate	SE	Estimate	SE
β ₀	5.5443	0.0251	4.756	0.0783
β_1	0.2063	0.006	_	_
β_2	-0.0005	0	0.001	0.0001
β_3	-142.365	2.4836	-33.8352	4.5894
β₄	-8.0154	0.5206	-1.8747	0.4295
β_5	0.0771	0.0029	-0.02	0.0067
$C_{\rm D}$	1.0745	_	1.0117	_
R^2	0.415	_	0.3741	_

Note: SE, standard error.

within FMAs was above 90% in most FMAs and decreased below this value in certain FMAs located in the northern and central portions of the boreal forests, in mountainous areas of British Columbia, and in Newfoundland (Fig. 3A).

Mean observed 10-year harvest rate H (eq. 4) was generally of 0.5% or less, except in some FMAs in central British Columbia where postepidemic salvage harvesting may have generated additional harvesting activities (Fig. 3B). By contrast, the theoretical harvest rate without fire $H_{\rm T}$ (eq. 3) was generally 1% or greater, with higher values found as expected in the more productive southern FMAs and lower values in the more northern portions of the boreal forests, in the northern cordillera region of British Columbia, and in Newfoundland (Fig. 3C). Conversely, the FMAs' mean age at maturity $(A_{\rm M})$ varied between 50 and 133 years (Fig. 3C). The relative harvest intensity without fire $(H_R; i.e., the$ ratio of H to H_T) was generally less than 75% across Canada, except in a few FMAs in central British Columbia and Alberta where values between 75% and 125% were reached (not shown). Therefore, should fire be totally excluded from the landscapes, most FMAs would be in the low vulnerability class with harvest rates at 2001-2010 levels.

Adding the fire risk of the current burn rate reduced the theoretical harvest intensity $H_{\rm TF}$ (eq. 6) for FMAs located in the HFR zones with more intense fire activity. FMAs with a large hardwood component were unaffected, but those in the conifer-dominated northern and western portions of the boreal forest saw large drops in their value of $H_{\rm TF}$. However, overall, the introduction of current burn rate into the calculation of the relative harvest intensity with fire ($H_{\rm RF}$) did not change the FMA vulnerability ratings as compared with calculations without fire (Fig. 4A). By contrast, recalculation of $H_{\rm RF}$ using the 2004 maximum yearly harvest rate $H_{\rm MAX}$ raised the vulnerability values of many FMAs in central Quebec into the moderate vulnerability range ($H_{\rm RF}$ from 0.75 to 1.25) (Supplementary Material S3¹).

Introducing the projected increases in burn rates for periods 2011 to 2040, 2041 to 2070, and 2071 to 2100 depressed the values of $H_{\rm TF}$ in all FMAs for these periods, with the smallest reductions in southern FMAs where future increases in burn rates are projected to be the least (Supplementary Material S3, S4, and S6¹). As a result, values of $H_{\rm RF}$ projected for these future periods rose in many FMAs, suggesting that their current mean harvest rate on an area basis would become increasingly vulnerable to fire (Figs. 4B, 4C, and 4D). Projected increases in burn rates from one period to the next only moderately increased the number of FMAs identified as vulnerable but tended to strongly increase the level of vulnerability in those FMAs that were identified as vulnerable in the earlier periods (Supplementary Material S3, S4, and S6¹).

Using H_{MAX} instead of H increased the number of FMAs with a vulnerability rating of moderate or higher and increased the level of vulnerability in those FMAs that were at least moderately vulnerable when calculations were performed using the mean H (Supplementary Material S4 and S6¹). Using H_{MIN} had the reverse effect, decreasing the level of vulnerability in BMAs and thus

Fig. 3. FMA-level values of (A) percentage of productive forest, where productive means that the forest is estimated to grow to 100 m³·ha⁻¹ in less than 200 years, (B) mean yearly harvest rate (H, % of area)), and (C) yearly theoretical harvest rate (H_T, %) and mean pixel age at maturity ($A_{\rm M}$). See Supplementary Material S6¹ for a larger representation of individual panels.



reducing the number of FMAs classified as having a moderate to higher vulnerability (Supplementary Material S3 and S6¹). By contrast, moving from the moderate RCP4.5 climate projection to the more extreme RCP8.5 climate projection for the 2071–2100 period had only a modest effect on vulnerability levels and failed to push

Fig. 4. Vulnerability classes using the mean harvest rate (2001–2010) under (A) the current fire regime, (B) the projected 2011 to 2040 fire regime under RCP8.5, (C) the projected 2071 to 2100 fire regime under RCP4.5, and (D) the projected 2071 to 2100 fire regime under RCP8.5. Vulnerability classes: low, $0 < H_{RF} \le 0.75$; moderate, $0.75 < H_{RF} \le 1.25$; high, $1.25 < H_{RF} \le 2$; extreme, $H_{RF} > 2$. See Supplementary Material S6¹ for a larger representation of individual panels.



additional FMAs out of the low vulnerability class into classes of higher vulnerabilities (Fig. 4; Supplementary Material S3, S4, and S6¹).

Finally, we evaluated the extent to which forest growth would need to change to bring the vulnerability of each FMA to the threshold between low and moderate vulnerability ($H_{\rm RF}$ = 0.75) for the most extreme scenario (RCP8.5) in the 2071 to 2100 period. This meant increases in forest growth for FMAs with moderate to extreme vulnerability and decreases in forest growth for FMAs already with low vulnerability. Results suggest that growth would have to increase by a factor of about 1.2 for FMAs with a moderate vulnerability rating, up to a factor of 3 or greater for the FMAs with an extreme vulnerability rating, to be brought down to threshold between low and moderate vulnerability (Fig. 5; see also colour version in Supplementary Material S6¹). Results also suggest that many FMAs would see their vulnerability rating increase from low to moderate with a drop in productivity of less than 25% (Fig. 6; see colour version in Supplementary Material S6¹).

Discussion

Vulnerability and adaptation

The results of our study suggest that the current vulnerability of timber supply to projected fire regimes is low in most FMAs but increases dramatically in a small number of FMAs across Canada under projected fire regimes. In general, high or extreme vulnerability occurs in FMAs in which current tree growth is slow, projected increase in burn rate is significant, and harvest rate is close to the theoretical harvest rate. The analysis also shows that vulnerability rises to the moderate level as early as in the 2011 to 2040 period for FMAs in which extreme vulnerabilities are calculated for the 2071 to 2100 period, indicating that these may already be at greater risk of fire-induced timber shortfall than most FMAs.

Growth increase under the effect of climate change could be seen as having the potential to offset some of these vulnerabilities, whereas growth decreases may increase the vulnerability of FMAs estimated as having a low vulnerability. Our results suggest that average growth would need to increase by at least 50% in most of the vulnerable FMAs and even double or more in extreme cases to offset the increased fire risk. Such large increases in growth are unlikely. In fact, many studies suggest reductions (Girardin et al. 2014; Lapointe-Garant et al. 2010; Girardin et al. 2008) or, at best, modest increases (Girardin et al. 2012) in growth in most of the boreal regions of Canada in the coming decades as a result of climate change. Such decreases in growth may push many FMAs from the low into the moderate vulnerability class (Fig. 6).

We present the results in terms of vulnerability of timber supply to current and future fire regimes. Within the context of climate change adaptation, the Intergovernmental Panel on Climate Change (IPCC) (2007) defines vulnerability as "the degree to which



Fig. 5. FMA-level factor by which current growth in FMAs with moderate to extreme vulnerability would have to be multiplied to lower them to the low vulnerability threshold of H_{RF} = 0.75 for the 2071 to 2100 period under RCP8.5. Hatched zones represent FMAs with low vulnerability in 2071–2100. See Supplementary Material S6¹ for a colour version of this figure.

Fig. 6. FMA-level factor by which current growth in low vulnerability FMAs would have to be multiplied to push them up to the moderate vulnerability threshold of H_{RF} = 0.75 for the 2071 to 2100 period under RCP8.5. Higher values indicate that only a modest decrease in growth would be needed to push these FMAs to the threshold. Hatched zones represent FMAs with moderate to extreme vulnerability in 2071–2100. See Supplementary Material S6¹ for a colour version of this figure.



a system is susceptible to, and unable to cope with, adverse effects of climate change". The use of this term in the present work supposes an inability to cope with these adverse effects of climate change, but in reality, options exist for coping with current and future fire risks within timber supply planning, many of which have been identified by Gauthier et al. (2014, their table 5). Some of these options are discussed below.

Improving fire suppression is proposed as a way to mitigate future fire risks (Gauthier et al. 2014). However, although some improvement in firefighting efficacy could be possible (see Cumming 2005), it is unlikely that it would succeed in addressing the projected increase in extreme fire weather conditions (Podur and Wotton 2010) and the related increase in fire number to reduce vulnerabilities in a significant way. Therefore, as fire risk will remain important in the future, its inclusion in all aspects of forest management is suggested as a no-regret adaptation option. These aspects include, for example, timber supply planning, managing for "fire-smart" landscapes, contingency planning for salvaging burned areas, and planning for a variable timber supply.

The inclusion of present and future fire risks in timber supply planning usually results in the reduction of the planned timber supply (Boychuk and Martell 1996; Leduc et al. 2015). However, as found by Leduc et al. (2015), when the existing fire risk is not taken into consideration, the fire-related periodic timber shortfalls will ultimately reduce the harvest realized over the planning horizon to a level below the planned timber supply. The real cost of including fire risk in timber supply calculations is therefore not equal to the drop in planned timber supply, but rather to the usually smaller drop in realized harvest over the planning horizon. This in turn has the benefit of an increased probability of a more stable timber supply for local economic activities (Leduc et al. 2015).

The concept of fire-smart landscapes (Hirsch et al. 2001) involves the creation of fire breaks through the promotion of deciduous forests. Recent work by Girardin and Terrier (2015) suggests that in some regions, a relatively modest annual increase in deciduous forest composition could reduce the vulnerability to future fire risk, provided that the regional soil and climate conditions are favourable for such a species shift.

Increased use of salvage logging is a no-regret adaptation option because of its multiple benefits under various risk levels (Gauthier et al. 2014). In many jurisdictions across Canada, following a large disturbance, harvesting is already redirected to accessible areas where timber is eligible for commercial harvesting. However, as found by Leduc et al. (2015), salvage logging cannot totally mitigate timber losses to fire, and its mitigation efficiency is highly dependent on a number of factors, including the age-class distribution of the burned forest stands and the burned fraction of the landscape. Technical issues such as accessibility of burned areas and degradation of standing dead trees over time also limit the potential of this option in areas subjected to high burn rates.

Limitations and uncertainties

Sources of bias in the present analysis are numerous but, in general, would tend to generate an underestimation of vulnerability in our assessment. We underestimate the current harvest rates because the MODIS-based disturbance maps generated by Guindon et al. (2014) capture only 75% to 80% of actual harvested areas. We also likely overestimate the area that is available for harvest within FMAs by not accounting for the so-called "netdowns" for land on which harvesting is totally or partially excluded through regulations or allocation to non-timber use. Both biases would lead to an underestimation of the relative harvest rates $H_{\rm R}$ and therefore of the vulnerability rating of the FMAs.

Similarly, biases related to fire interannual variability and to the stand age-class structure would also tend to result in an underestimation of vulnerability. We underestimate the impact of fires on timber supply by representing them in a deterministic manner in eqs. 5 and 6 instead of a more realistic stochastic manner, as found by Boychuk and Martell (1996). We also overestimate the theoretical harvest intensity by basing its calculation on a regulated (also called "normal") age-class distribution, which under controlled conditions yields the largest possible sustained timber yield (Bettinger et al. 2008). Age-class distributions across Canada's extensively managed natural forests deviate significantly from this ideal because of natural disturbances (Van Wagner 1978) and will therefore generate a lower sustained yield. As a result, our calculations overestimate the theoretical harvest rates $H_{\rm T}$ and underestimate the relative harvest rates $H_{\rm R}$, which leads to an underestimation of timber supply vulnerability to fire.

A central aspect of this analysis is the evaluation of pixel-level tree growth from the forest properties estimates, but these properties have documented biases related to the averaging nature of the underlying procedures (Beaudoin et al. 2014). In spite of this, the pixel-level growth estimations based on these properties seem to provide reasonable estimates of FMA-level mean growth. Values of $H_{\rm T}$ can be translated directly into mean annual increments (MAI, m³·ha⁻¹·year⁻¹) as they express the percentage of territory that, on average, reaches 100 m³·ha⁻¹ each year. Hence, a value of 2%-year-1 of harvest intensity of stands that have reached commercial maturity means that the MAI of these stands averages 2 m³·ha⁻¹·year⁻¹. When viewed from that perspective, Fig. 3C shows that the mean FMA-level MAIs in the area under study vary between 0.75 and 2 m³·ha⁻¹·year⁻¹. These values compare generally well with the Canada-wide inventory-based evaluation by Bickerstaff et al. (1981) in which the MAI values of their "forest sections" covering our FMAs also vary within the same bounds and show comparable spatial patterns (Supplementary Material S51). Such a convergence between two completely different products gives confidence in the present evaluation of $H_{\rm T}$ estimates.

The level of FMA-level vulnerability to losses by fire is highly dependent on the rate of timber harvest. Our analyses, using the highest and lowest harvest rates encountered within the 10-year window of the analysis, suggest that the extent of vulnerable FMAs is more sensitive to changes in harvest rates than to differences among RCP-based fire scenarios (Supplementary Material S3, S4, and S6¹). The future demand for forest products would therefore have a significant effect on the level of future vulnerability of FMA timber supply to fire risk.

Assumptions with respect to fire dynamics and lack of vegetation responses were also made to simplify the analysis. We assumed that fire acted as a random process over the landscape, but recent work (Héon et al. 2014) suggests that young forests have lower probabilities of burning, with potential impacts on timber supply. Such fire preferences would increase competition between fire and harvesting for timber and, therefore, also increase the vulnerability estimates as compared with those computed here, particularly where regional burn rates are above 1% (Gauthier et al. 2015; see Supplementary Material S1¹). More importantly, however, this analysis assumes that postdisturbance regeneration and composition will be stable. However, sequences of events unfolding within the context of a changing climate may change regeneration dynamics (Jasinski and Payette 2005; Van Bogaert et al. 2015), thereby adding to the overall uncertainty of the vulnerability projections in this analysis.

The present analysis deals only with fire as a disturbance. Other natural disturbances, and especially insect outbreaks whose regimes are also be affected by climate, may also impact timber supply, either in areas identified as vulnerable to fire in the current analysis or in other areas of the managed forests. For example, Hennigar et al. (2013) suggest that the absence of adaptation or mitigation measures to projected levels of spruce budworm (*Choristoneura fumiferana*) defoliation could generate harvest reductions of 25% in the province of New Brunswick by 2052. Mortality or growth reductions due to drought are also predicted to increase (Michaelian et al. 2011; Girardin et al. 2008) and may affect timber supply locally or regionally. Other regional events such as ice or wind storms (Bouchard et al. 2009; Larson and Waldron 2000) may also have significant local impacts on timber supply.

Conclusion

In spite of all of the limitations described above, the analysis identifies in relative terms where, when, and to what extent timber supply could be most vulnerable to projected increases in the most common and widespread natural disturbances in the boreal and montane forests of Canada. This knowledge may help support forest managers in their efforts towards adoption of adaptation measures to climate change. It is clear, however, that areas identified as having a low vulnerability in our analysis should still be subjected to risk analysis and adaptation actions.

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