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ARTICLE

Using salvage logging and tolerance to risk to reduce the impact of forest fires on timber supply calculations

A. Leduc, P.Y. Bernier, N. Mansuy, F. Raulier, S. Gauthier, and Y. Bergeron

Abstract: It is acknowledged that natural forest fires cannot and even should not be eliminated from the North American boreal forest. Forest fires produce immediate losses of wood volume, disrupt the conversion of the actual forest age structure into a target structure, and prevent planned timber supply (PTS) levels from being achieved. In this paper, we explore the extent to which periodic shortfalls in available timber under various burn rates can be mitigated through salvage logging and the tolerance of forest managers to a given level of shortfall, both as a function of forest age class structure. Simulations are done using both a deterministic and a stochastic representation of burn rate over time. Results show that the frequency of shortfall events can be reduced by salvage logging and by the introduction of measures that generate a tolerance to shortfall and that this mitigation potential is influenced by initial forest age class structure and burn rate. Results also show that even a 100% rate of salvage logging cannot fully compensate for timber losses to fire and eliminate fire-induced timber shortfalls. Furthermore, interannual burn rate variability reduces the efficiency of both mitigation measures. As the PTS is never realized under fire risk, the real cost of opting for different PTS scenarios should be estimated not from the difference in PTS but rather from the more realistic difference in realized timber harvest.

Key words: natural disturbances, sustained yield, boreal forest, stochastic processes.

Résumé : Il est reconnu que les feux de forêt d'origine naturelle ne peuvent pas et même ne doivent pas être éliminés de la forêt boréale nord-américaine. Les feux de forêt occasionnent des pertes immédiates de volume de bois, perturbent la conversion de la structure courante d'âge de la forêt vers une structure cible et empêchent l'approvisionnement planifié en bois (APB) d'être atteint de manière constante. Dans cet article, nous explorons dans quelle mesure les déficits périodiques en bois disponible causés par divers risques de feux peuvent être atténués par la coupe de récupération et par le degré de tolérance des gestionnaires forestiers face à ces déficits, et ceci en fonction de la structure d'âge des forêts. Les simulations sont faites en utilisant une représentation temporelle déterministe et stochastique des feux. Les résultats montrent que la fréquence des périodes en déficit de bois peut être réduite par la coupe de récupération et par l'introduction de mesures de tolérance à ces déficits, et que ce potentiel d'atténuation est influencé par la structure d'âge de la forêt initiale et par le niveau de pertes par le feu. Les résultats montrent également que même un taux de coupe de récupération à 100 % ne peut pas compenser entièrement les pertes de bois par le feu et éliminer les déficits périodiques qui en résultent. En outre, l'ajout de la variabilité interannuelle des feux réduit l'efficacité des deux mesures d'atténuation. Enfin, puisque l'APB n'est en fait jamais réalisé dans les forêts sujettes aux feux, le coût réel d'une réduction l'APB doit être estimé non pas par la différence l'APB, mais plutôt par la différence plus réaliste de récolte de bois réalisée.

Mots-clés : perturbations naturelles, rendement soutenu, forêt boréale, processus stochastiques.

Introduction

In the boreal forests of North America, fires may cause important losses of goods and services, including timber supply (Van Wagner 1983; Martell 1994). Meanwhile, total fire exclusion is not only economically unrealistic but also ecologically questionable (Hirsch et al. 2001). Fires will, therefore, continue to affect forest goods and services, but because their occurrence remains largely unpredictable in the short term for a given area, it is unrealistic to incorporate their potential effect into short-term planning. However, the spatial and temporal scope of strategic forest management planning, often spanning 100 years or more for territories covering thousands of square kilometres, provides a favourable framework for including fire risk. Strategic forest management planning is performed to ensure that, to the best of our knowledge, planned human activities, including the harvest of timber, do not endanger the sustainability of the goods and services provided by the forest as defined within a sustainable management framework (Harvey et al. 2003).

In the particular case of timber, sustainability of its supply (i.e., planned timber supply, henceforth PTS) is usually calculated as the maximum constant level of harvest that can be sustained across the planning horizon during which fluctuations in available timber volume are predicted to occur. The calculation over the full planning horizon is usually performed by 5- or 10-year periods, and assuming a constant PTS, its upper bound is, therefore, the smallest available volume of timber of any period during that planning horizon. The predicted fluctuations of available timber volume through time are mostly due to the initial forest age structure, to the harvesting itself, and to a lesser extent, to the speed of tree growth. At some future time, natural disturbances

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such as fire may alter the forest age class structure and decrease the expected timber volume that should be available for harvest at a given period. Not accounting for future fire may, therefore, result in the occurrence of one or many periods during which there is less timber available for harvest than what had been planned through the PTS calculations.

A number of studies have already pointed to the importance of accounting for potential losses in forest planning caused by future forest fires (Van Wagner 1983; Reed and Errico 1986; Boychuk and Martell 1996; Armstrong 2004; see Bettinger (2010) for a review). Accounting for such potential losses necessarily entails a reduction of the planned harvest level to create a buffer stock of timber (Boychuk and Martell 1996) and such a reduction may be substantial. Van Wagner (1983) concluded that reductions in timber supply would vary from approximately 15% to 50% when considering burn rates ranging from low (<0.5% of the management unit per year) to high (>2% per year). Reed and Errico (1986) estimated that a 40% reduction would be required to account for an annual burn rate of 1% per year, whereas Martell (1994) calculated that a 35% reduction would be required to account for a mean annual burn rate of 1.5% per year. Given these large impacts on the PTS, and therefore on the immediate harvest rate, managers prefer to account for losses through a posteriori adjustments to the calculations. However, this may be insufficient to compensate for the omission of fire from long-term planning (Savage et al. 2010).

Mitigation strategies exist for managing the impact of fire inclusion in PTS calculations. One of these lies in the notion of tolerance to risk (Gardiner and Quine 2000), which, in analogy with the insurance industry, drives the cost of insurance policies (Armstrong 2004; Peter and Nelson 2005). In the case of forest management and fire, we define tolerance to risk (or tolerance to shortfall) as the acceptable shortfall intensity, i.e., the maximum level of timber shortfall, with respect to the calculated PTS, that a manager is willing to accept during any given period over the planning horizon (Armstrong 2004; Peter and Nelson 2005). Any increase in a manager's tolerance to risk will also automatically reduce the shortfall frequency, i.e., the number of intolerable shortfalls that will occur over the planning horizon. The cost of the policy for reducing the shortfall frequency is the reduction in PTS that a forest manager is willing to accept over the full planning horizon. We propose that the inclusion of tolerance to risk is one possible tool to reduce the impact of fire inclusion in PTS calculations.

Another mitigation strategy is the salvage of burned timber (Peter and Nelson 2005). If fire were to systematically "harvest" the older age classes as timber harvest does, salvaging 100% of burned forests would eliminate the need to account for fire in forest planning. However, in North American boreal forests where crown fires are most frequent, fire appears to burn age classes indiscriminately (Bessie and Johnson 1995). As a result, the proportion of the burned area eligible for salvage logging is a function of the preburn forest age class structure and, hence, a function of preburn availability of mature harvestable stands. We propose that the use of salvage logging should also help mitigate the inclusion of fire within PTS calculations but that this mitigation capacity will be positively related to the proportion of mature and overmature forest stands in the landscape.

Therefore, in this study, we investigated the extent to which the two mitigation strategies proposed above may help mitigate the inclusion of fire within PTS calculations and how this mitigation potential will be affected by initial forest age structure and burn rate. Our initial hypotheses were that (*i*) salvage logging in any circumstance can mitigate but not wholly compensate for periodic timber shortfalls, (*ii*) the efficiency of salvage logging in reducing the importance and frequency of shortfalls during the planning horizon increases with the proportion of harvestable stands in the landscape, and (*iii*) accounting for the forest manager's tolerance to risk will also help reduce the expected frequency of shortfalls; however, the efficiency of this measure will decrease with increased burn rate. In the remainder of this text, we use black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.) as our model species for boreal fire-prone forests, but the overall approach is applicable to commercial boreal fire-prone forests of any composition.

2. Methods

2.1. Simulating PTS and fire

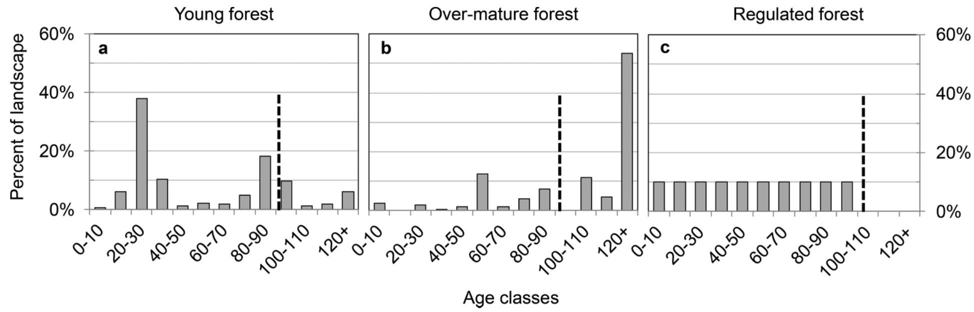
We used a simulation model to project volumes of available timber over time under different burn rates from which we could extract the PTS. This model is similar in many ways to the one developed by Van Wagner (1983), and its main properties are as follows: (*i*) the timber productive area of a forest management unit (FMU) is composed of a single stand type characterized by a single yield curve over time; (*ii*) time periods (intervals) are discrete (i.e., 10 years) and correspond to the age classes used to describe the forest age structure of the FMU; (*iii*) postfire and postharvest regeneration begins without delay in the 0–10 year age class; (*iv*) all stands have an equal burning probability, irrespective of their age, and that probability is expressed as a burn rate (average percentage of the territory burned per year); (*v*) stands that exceed the age of commercial maturity lose wood volume due to senescence, following the yield table of Pothier and Savard (1998) for black spruce stands (*P. mariana*) and assuming a site index of 12 m at 50 years and a medium stand density; (*vi*) minimum rotation age is set at 100 years, at which point the commercial volume is of 90 $m^3 \cdot ha^{-1}$, therefore providing a theoretical maximum PTS of 0.9 $m^3 \cdot ha^{-1} \cdot year^{-1}$ for a fully regulated forest; (*vii*) PTS is equated to a sustained-yield harvest rate and represents the periodic (10-year) harvest rate on a 250-year time horizon; (*viii*) for ease of scenario analysis and comparison, no social or ecological constraints are considered within the timber production area; and (*ix*) the simulation is not spatially explicit.

The model is initiated by way of a vector describing the timber productive area per age class. The vector contains 12 + 1 ten-year age classes, with the last one acting as a sink (120 years and more). The sum of this vector equals one surface unit, which, in this case, may represent a full forest management area. Each age class can, therefore, be seen as occupying a certain percentage of this timber productive area. A volume-based target level of harvest is chosen. Processing at each 10-year time step is conducted in the following sequence:

(1) Fire is allowed to burn a set proportion of the landscape, distributed with equal probability among each age class as a function of their landscape distribution.
(2) Burned areas in age classes with commercial timber volume are then subjected to salvage logging at a preset rate.
(3) Volume to be harvested, calculated as the PTS harvest level minus the volume recovered through salvage logging, is subtracted from the volume available in the oldest age classes, having met or exceeded the age of commercial maturity. A negative value is a shortfall.
(4) The area-per-age-class vector is updated at the end of each simulation cycle by assigning areas burned or harvested to the 0–10 year age class and assigning all other areas to the next 10-year age class. The cycle was repeated 25 times, resulting in a 250-year simulation period.

In the following analysis, a shortfall occurs when the periodic harvestable volume is below the PTS. We define the frequency of shortfalls as the number of 10-year periods during the 250-year simulation horizon that experience a timber supply shortfall and define the intensity of a shortfall as the difference between the PTS and the periodic harvestable volume. The tolerance to shortfall was implemented by discarding from the shortfall frequency calculations all periods during which the intensity of shortfall was

Fig. 1. Stand age class distributions used in the simulations for (*a*) young, (*b*) overmature, and (*c*) theoretical, fully regulated forest landscapes. The vertical dashed line at age = 100 years represents the start of the mature, harvestable age classes.



lower than a preset level of tolerance. The model was implemented in the R programming language (http://www.r-project.org/).

2.2. Scenario modelling

Three contrasting initial forest age structures were tested in the simulations (Fig. 1). A young forest age structure is taken from the southern half of a FMU in the Abitibi region (Quebec, Canada) that has been intensively harvested since 1970 (Belleau and Légaré 2009), with 9% of the productive area still covered by stands eligible for harvest as of 2000. The overmature forest age structure is taken from a currently unmanaged forest landscape in the North Shore region (Quebec, Canada; Cyr et al. 2007) in which a typical 69% of the productive area is covered by stands eligible for harvest. Both of these existing landscapes are dominated by black spruce. The reference age structure is that of a theoretical, fully regulated forest with a rotation age of 100 years.

We tested two levels of both mitigation strategies. In our simulations, salvage logging was set at either 0% or 100% of burned merchantable timber volumes (up to the PTS value). Tolerance to shortfall was also varied, taking on values of 0% or 20% of the PTS in the various scenarios. We chose the 0% and 100% rates for salvage logging, because they capture extreme policy choices and, therefore, provide bounds to the impact of all possible alternatives. We chose the 0% and 20% tolerances to shortfall, because they were deemed to represent reasonable bounds of applicability. As an example, the tolerance to shortfall could represent the capacity for a given mill to source its timber from an alternate land base for a given period.

Finally, we applied three different burn rates in our simulations: 0.666% per year, which corresponds to a 150-year fire cycle; 0.285% per year, which corresponds to a 350-year fire cycle; and 0.100% per year, which corresponds to a 1000-year fire cycle. These three rates represent the range of values currently found in the commercial black spruce – moss forests of northeastern Canada (Bergeron et al. 2006; Mansuy et al. 2010).

The simulations were carried out with fire included as either a deterministic or stochastic event. For the deterministic simulations, we kept the burn rate constant in all periods across the simulation horizon. For the stochastic simulations, we first extracted 55 ten-year sequences (1940–1949, 1941–1950, …, 1994–2003) of decadal burned areas within landscape units (Robitaille and Saucier 1998) of about 5000 km² in the commercial public forest of Quebec from the fire data records of the Ministère des Ressources naturelles du Québec. These decadal values were then scaled to yield a vector of scaling factors centred on one. We then ran 1000 simulations for each combination of age structure, salvage logging rate, burn rate, and tolerance to shortfall, while randomizing decadal burn rate scaling factors each time. Therefore, the fire's area stochastic events and the stochastic representation should provide a more realistic representation (Armstrong 1999). However, presenting results for deterministic simulations may be relevant to forest management agencies with optimization-based PTS calculators that are not easily amenable to the inclusion of stochastic processes.

2.3. Comparing scenarios using risk curves

For each combination of factors, we built “risk curves” relating the shortfall frequency to the PTS by varying the PTS from 0.6 $m^3 \cdot ha^{-1} \cdot year^{-1}$ to a maximum harvest rate of 1.1 $m^3 \cdot ha^{-1} \cdot year^{-1}$ in steps of 0.1 $m^3 \cdot ha^{-1} \cdot year^{-1}$. Lowering the PTS to values smaller than the maximum PTS level of 1.1 $m^3 \cdot ha^{-1} \cdot year^{-1}$ represented the “cost of the insurance policy”. This maximum harvest rate was set so as to slightly exceed the PTS of 0.9 $m^3 \cdot ha^{-1} \cdot year^{-1}$, computed by applying the black spruce yield curve used in the present study to a fully regulated forest without natural disturbance (Buongiorno and Gilless 2003). For the stochastic fire regime simulations, the risk curves were built by considering the medians of the periodic cumulated frequency distribution of shortfalls for each level of PTS.

Finally, each scenario was compared with its worst-case scenario, which was made up of a regulated forest submitted to an equivalent burn rate, with no salvage logging and no tolerance to shortfall. For this purpose, the area below each risk curve (risk area) was numerically estimated and compared with the risk area calculated for its worst-case scenario. Results are presented as a mean percent reduction in the shortfall frequency of the worst-case scenario.

3. Results

As expected, results across all nine combinations of age structures and burn rates show that the shortfall frequency over the planning horizon, used here as our measure of risk, is greatest when neither salvage logging nor tolerance to risk are used as mitigation measures. This holds true for both deterministic (Figs. 2 and 3) and stochastic (Fig. 4) simulations. This means that, for a given value of PTS, the absence of any mitigation measure will result in the greatest number of periods with timber shortfalls. Conversely, to respect a given maximum frequency of shortfall periods, the scenario without mitigation measures will also have the lowest value of PTS.

The application of the two mitigation strategies, 100% salvage harvesting and 20% shortfall tolerance, lowers the shortfall frequency in nearly all combinations of age structures and burn rates and in both the deterministic and stochastic simulations. However, and not surprisingly, 100% salvage harvesting is not an effective mitigation measure in the scenarios with the lowest burn rate (Figs. 2*c*, 2*f*, and 2*i*). The efficiency of this measure increases dramatically with both increasing burn rate and increasing proportion of overmature stands (Fig. 2*d*), as both combine to provide burnt merchantable timber on the landscape. The tolerance to risk, our second mitigation measure, behaves in a reverse manner, being more effective in low burn rate scenarios. Although not totally additive, the effects of both mitigation measures when used simultaneously predictably lower the shortfall frequency to

Fig. 2. Risk curves showing the percentage of 10-year periods with timber shortfalls within the 250-year planning horizon as a function of levels of planned timber supply (m³·ha⁻¹·year⁻¹) for scenarios with 20% tolerance to shortfall (T), 100% salvage logging (S), both S and T (S+T), and neither S nor T (no label) for the three forest age class structures (young (*a*, *b*, *c*), overmature (*d*, *e*, *f*), and regulated (*g*, *h*, *i*)) and the three burn rates (0.67 %·year⁻¹ (*a*, *d*, *g*), 0.29 %·year⁻¹ (*b*, *e*, *h*), and 0.10 %·year⁻¹ (*c*, *f*, *i*)), as simulated using a deterministic simulation of fire occurrence.

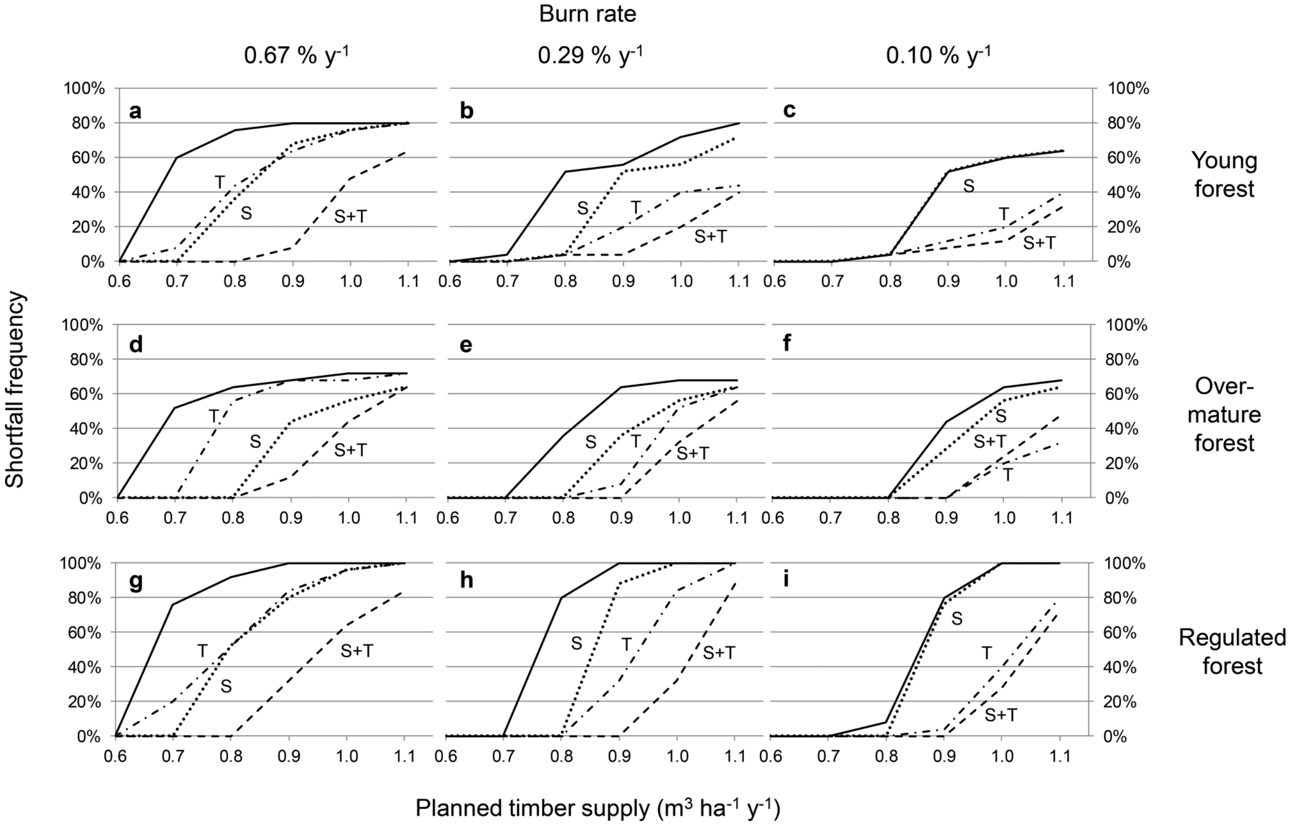
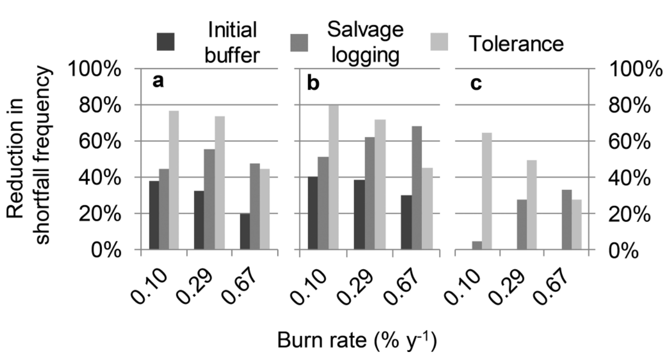


Fig. 3. Mean reduction in shortfall frequency, as modeled from the deterministic simulation of burn rate (%·year⁻¹), resulting from the difference in age class structure (initial buffer), salvage logging, and tolerance to a 20% timber shortfall. The reduction is expressed as a percentage of the shortfall frequency estimated for the worst-case scenario of regulated forest submitted to an equivalent burn rate with no salvage logging and no tolerance to shortfall for (*a*) young forest, (*b*) mature and overmature forest, and (*c*) regulated forest.



below 10% for PTS values of 0.9 m³·ha⁻¹·year⁻¹ across almost all scenarios in both the deterministic and stochastic simulations, with the exception of the regulated forest with the highest burn rate (Fig. 2*g*).

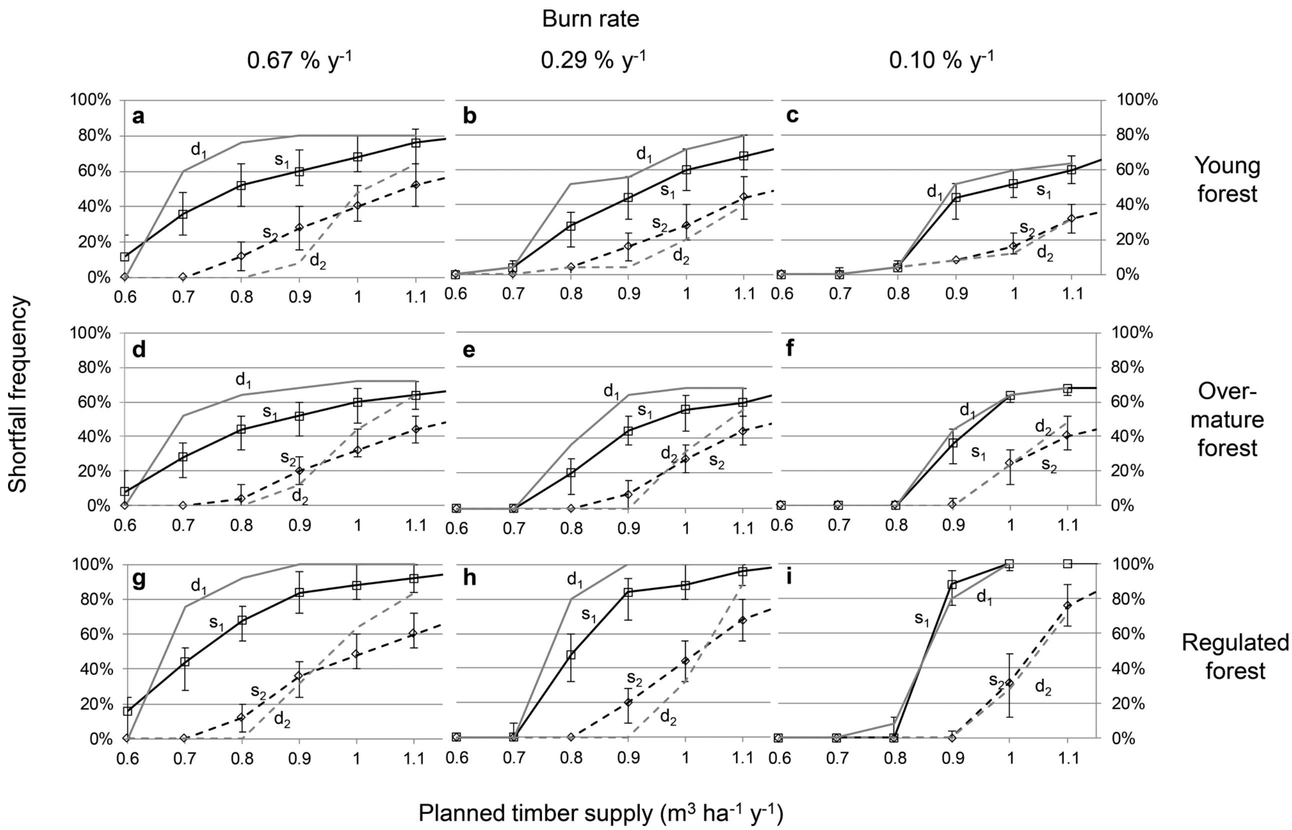
Forest age structure has a major effect on the relationship between PTS and shortfall frequency (Figs. 2 and 3). In the regulated forest, in the absence of mitigation measures, all three burn rates push the shortfall frequency to 100%, with a PTS at or above its optimal value of 0.9 m³·ha⁻¹·year⁻¹ (Figs. 2*g*–2*i*). In comparison, the shortfall frequency is lower in the overmature forest for any combination of fire frequency and mitigation measures. The young forest structure provides an intermediate case. Despite these points, forest age structure by itself cannot completely eliminate shortfalls (Fig. 3), because PTS values that achieve this level of risk are the same for the three forest structures and depend mostly on the burn rate (Figs. 2 and 4).

An increased burn rate results in an increased frequency of shortfalls at any level of PTS. The effect, however, is more pronounced in the deterministic simulations (Fig. 2) in which the frequency of shortfall rises sharply with an increased burn rate and PTS. In contrast, results from the stochastic simulations (Fig. 4) show a more gradual increase in shortfall frequency with increased PTS and lower values of maximum shortfall frequencies compared with those obtained in the deterministic simulations. The only exception is for the lowest burn rate (Figs. 4*c*, 4*f*, and 4*i*) in which both methods of simulation are almost equivalent. In addition, the inherently larger period to period variability in burn rate associated with stochastic simulations somewhat reduces the mean ameliorative effect of the combined mitigation measures on the shortfall frequency compared with the deterministic simulations (Fig. 4). In short, stochastic simulation of fire occurrence should better represent the range of possible futures, but the deterministic representation, with its gloomier picture, is often more compatible with the mechanics of PTS calculations performed by forest management agencies.

4. Discussion

As hypothesized, using salvage logging to limit wood losses caused by fire appears to be an efficient tool for mitigating the

Fig. 4. Risk curves for two combinations of mitigation options across the three forest age class structures (young (*a*, *b*, *c*), overmature (*d*, *e*, *f*), and regulated (*g*, *h*, *i*)) and the three burn rates (0.67 %·year^{-1} (*a*, *d*, *g*), 0.29 %·year^{-1} (*b*, *e*, *h*), and 0.10 %·year^{-1} (*c*, *f*, *i*)), as simulated using a stochastic (s) or a deterministic (d) simulation of fire occurrence. The lines show the following mitigation options: solid line, no salvage logging and (or) no risk tolerance (s_1, d_1); dashed line, 100% salvage logging and (or) risk tolerance up to 20% (s_2, d_2). Error bars represent the difference between the 5th and the 95th percentiles.



uncertainty in PTS related to natural disturbances such as fire, but its mitigation efficiency is directly related to the proportion of the landscape in mature and overmature stands (Fig. 3). More importantly, however, even if salvage logging appears very efficient, our analysis demonstrates that it cannot totally compensate for all such wood losses. By burning premerchantable stands, fire also disrupts the age class structure required to ensure the maximum sustainable yield envisioned by an even-aged management strategy (Buongiorno and Gilless 2003). This effect cannot be counteracted by salvage logging, and a priori adjustments in PTS are always required.

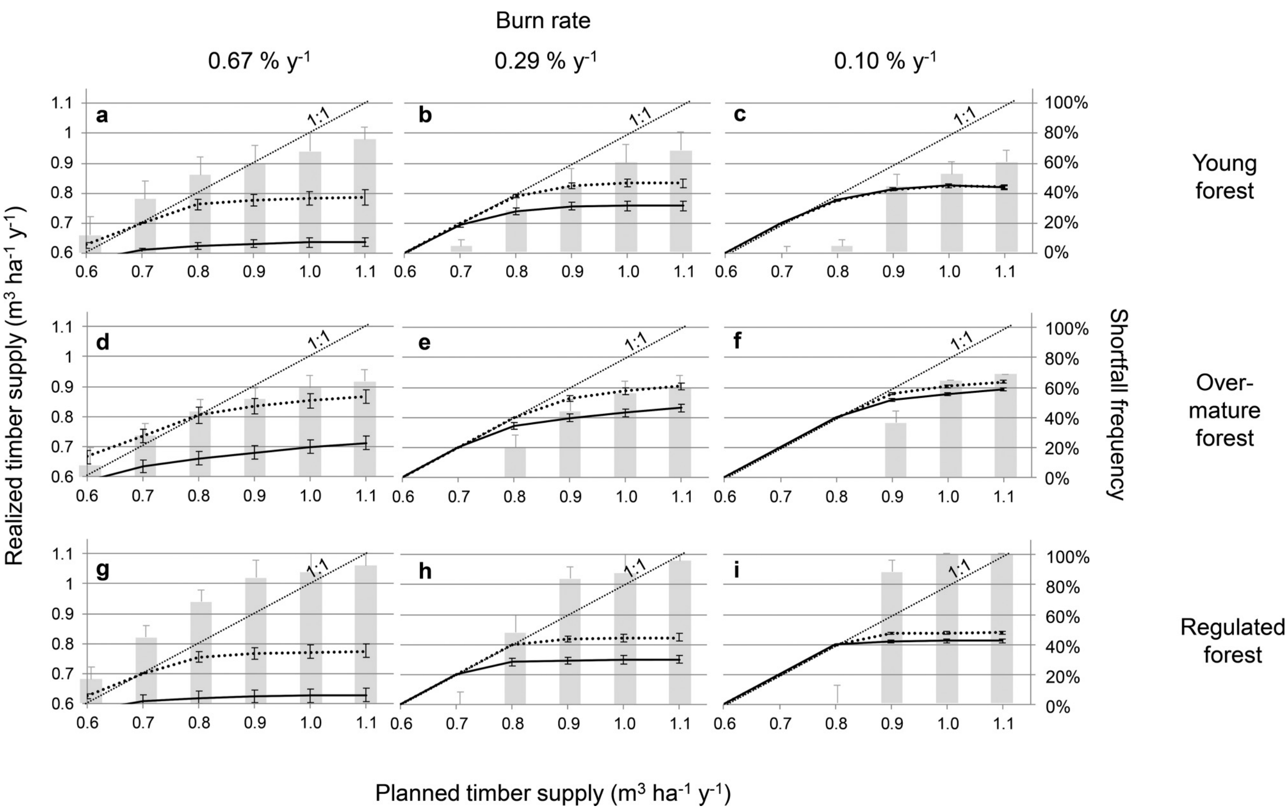
In addition, other factors may reduce the salvage logging potential in actual forest management or operations. In the boreal forests of Canada, fires of natural causes will occur randomly in the landscape with no relation to existing forest access. Given the sparse road networks of Canadian boreal forests, burnt timber in any given year, therefore, may be far from existing roads or be distributed in such a way within a given FMU as to be uneconomical to access. Delays mean a rapid degradation of timber value because of boring insects (Boulanger and Sirois 2007) and colouration from fungi and thus a drop in timber value.

Many studies have also shown the ecological importance of natural forest fires and of their postdisturbance biological legacies (Schmiegelow et al. 2006; Nappi et al. 2004; McCullough et al. 1998). Indeed, some have even questioned the use of the term "salvage" itself as if burnt timber served no purpose (Lindenmayer and Noss 2007). It is clear that in real forest management operations, both economics and ecology will act to constrain the salvage harvesting below the 100% used in this study, and regulations or subsidies to support this practice will have to account for such constraints.

The inclusion of risk in forest modelling is an issue that has been extensively studied, especially when linked with fire and climate change (see Yousefpour et al. (2012) for a review). Yet, the use of tolerance to risk as a mitigation tool remains poorly explored (Borchers 2005), although risk management is an inherent part of most other economic activities. Within a forest management context, the level of tolerance to risk has been related to, for example, the relative ease of accessing alternate means of wood procurement (Klemperer 1996; Davis et al. 2001), whereas the reduction in PTS to ensure a more constant timber supply could be related to, for example, a desire for local economic or manpower stability in forest-dependent communities. A relatively constant timber supply is also a proof of sustainability (see, for example, Montréal Process (2009) for North American boreal forests). However, as noted by Boychuk and Martell (1996) and Peter and Nelson (2005), a strict even flow of timber may be very expensive, if not impossible, to maintain when dealing with the uncertainties caused by fire. A balance is thus required between the risk incurred by planning over a very long time frame and the basic answers, including sustainability, that are awaited from the planning process. At this point, to our knowledge, neither the mechanisms nor the motivations surrounding the tolerance to risk of shortfalls have been clearly articulated within either the public or the private institutions involved in forest management in Canada, but both aspects must already exist in a more informal manner.

Our results support those from previous studies (e.g., Boychuk and Martell 1996) and suggest that, because of their large buffer

Fig. 5. Realized timber supply (m³·ha⁻¹·year⁻¹) with (100%, dotted line) or without (0%, solid line) salvage logging versus planned timber supply, as simulated using a stochastic simulation of fire occurrence across the three forest age class structures (young (*a*, *b*, *c*), overmature (*d*, *e*, *f*), and regulated (*g*, *h*, *i*)) and the three burn rates (0.67 %·year⁻¹ (*a*, *d*, *g*), 0.29 %·year⁻¹ (*b*, *e*, *h*), and 0.10 %·year⁻¹ (*c*, *f*, *i*)). Also shown (bars) are the shortfall frequencies as percentage of the 25 periods of the planning horizon, as well as the 1:1 line.



stock, forests with an overmature age class structure are less prone to shortfall than young and regulated forests. Because of their higher eligibility to salvage logging and lower susceptibility to regeneration failure (Le Goff and Sirois 2004; Jasinski and Payette 2005), landscapes dominated by mature and overmature stands also offer more management opportunities than those dominated by younger age structures. In a context of ecosystem-based management, increasing the relative importance of uneven-aged management in the boreal forest may help maintain or increase the proportion of stands with attributes of maturity or overmaturity, thereby reducing the difference between managed and natural forests (Bergeron et al. 2010; Gauthier et al. 2009). On the other hand, the explicit use of mature and overmature stands as buffer stocks against timber shortfalls will gradually deplete these age classes (analysis not shown). Maintenance of target levels of these older age classes on forest landscapes within an ecosystem-based management context may limit their use as part of a shortfall mitigation strategy.

In addition, recent studies have shown that the absence of stand establishment costs and a more favourable assortment distribution of harvested timber increases the profitability of uneven-aged stand management (Tahvonen 2009; Pukkala et al. 2010). Indeed, from an economic point of view, the profitability of uneven-aged forestry, compared with even-aged management, appears more obvious with increasing discount rates, increasing forest management costs, and decreasing timber prices (Pukkala et al. 2011). By reducing the time to recovery of mature forest stand conditions after harvesting and by decreasing the importance of young stands at the landscape level, uneven-aged management could be seen as an approach to mitigating the forest planning uncertainty generated by fire.

The utility of a priori inclusion of fire risk in PTS may be questioned by considering that recalculations of PTS are made every 5 or 10 years (Savage et al. 2010). Such recalculation allows the manager to adjust the FMU's PTS to new forest conditions generated by recent disturbance events, thereby constituting an important adaptation to the uncertainty of natural disturbances. Recently, however, Savage et al. (2010) showed that the use of periodic replanning fails to cancel the impact of fire on harvest volume variability. In addition, there is consensus that climate change will increase burn rates in numerous parts of the boreal forest (Boulanger et al. 2014; Flannigan et al. 2009), although the local magnitude of such an increase is highly uncertain. In the face of this uncertainty, an a posteriori management of fire risk results in a momentary overexploitation of forest resources and a necessary, and potentially larger, future reduction in harvest levels. Indeed, Boychuk and Martell (1996) came to the paradoxical conclusion that reducing the PTS could, in fact, yield larger total harvest volumes over the planning horizon through the avoidance of such larger periodic shortfalls. Further analyses of results from our simulations partially support this claim. In all of our scenarios, the increase in realized harvest is a progressively lower fraction of the increase in PTS, whereas shortfall frequencies keep on increasing (Figs. 2 and 5). As a corollary, decreasing the PTS, say from 0.9 m³·ha⁻¹·year⁻¹ to 0.8 m³·ha⁻¹·year⁻¹, results in a much smaller reduction in realized timber harvest. As the PTS is never realized under fire risk, the real cost of opting for different PTS scenarios should be estimated not from the difference in PTS but rather from the more realistic difference in realized timber harvest.

As outlined by Hoogstra and Schanz (2008), the main particularity of forest resource management is that it deals with time horizons that far surpass those considered in the management of other natural resources such as crop industries. Making predictions over such long time horizons involves a great deal of uncertainty and risk. Our results clearly illustrate the need for prudence when striving to effectively meet management targets, often expressed in terms of projected forest conditions. In present-day forest management, the notion of sustainability has expanded to embody a diverse collection of values and conditions characterizing the forest. In this perspective, it becomes imperative to adopt a forward-looking approach to forest management through an appropriate inclusion and mitigation of fire risk.

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