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Introducing two indicators for fire risk consideration in the management of boreal forests

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ABSTRACT

When forest fires are taken into account during timber supply analyses, planned harvest rates are necessarily reduced to prevent potential timber shortages due to future forest fires. Because fire events are highly unpredictable, forest managers are reluctant to proactively reduce harvest targets, as it results in an immediate revenue loss. We explored a simple but proactive way of including the risks and uncertainties of fire in forest management planning through the identification of low productivity forest areas most vulnerable to fire in two different boreal forest zones. Site index and relative density index were used to estimate the time required to reach different harvesting thresholds based on stem size and tree density. We varied the production objective by using three different thresholds of minimum stem size (dm^3/tree) and stand yield (m^3/ha) (50 dm^3/tree – 50 m^3/ha, 70 dm^3/tree – 70 m^3/ha, 90 dm^3/tree – 90 m^3/ha). We estimated the time required to reach these thresholds and the proportion of forest zone that could exceed them. Fire cycle length was then used to assess the survival likelihood (probability of reaching the threshold at the stand scale when considering fire risk). An alternative rate of return was also used as an indicator of profit exposure to fire risk. When survival likelihood and alternative rate of return are considered jointly with time-declining interest rates, minimum survival likelihoods need to be higher for longer fire cycles. The proportion of stands vulnerable to fire served to decide whether or not to include fire risk into strategic planning. The identification of major break points in the vulnerability assessment also helped to decide which minimum harvesting threshold is appropriate as a function of the productivity characteristics and fire cycle of the forest under management.

1. Introduction

Sustainability is now the overarching goal of forest management for many countries of the world. Since the Montreal Process (1995), forest management typically implies planning harvesting activities over a long time horizon while considering economic, environmental and social dimensions. In many forest biomes, fire is an important disturbance that interferes with timber availability, despite the fact that most jurisdictions have very good fire suppression systems (Pan et al., 2011). Fire activity is controlled by weather and climate, vegetation, human activities, and topography. Dry forest fuels and winds are major contributors to large stand-destroying fires (Flannigan and Wotton, 2001; Westerling et al., 2006). The strong linkage between historical forest fire activity and climate suggests that fire activity will still occur in the boreal forest and might be increasing in the face of climate change (Flannigan et al., 2009; Bergeron et al., 2006, 2010). Moreover, as climate variability is affecting the annual area burned (Girardin et al., 2009; Le Goff et al., 2008), forest fires represent highly variable and uncertain losses of timber supply. These uncertainties have hampered the inclusion of fire risk into the planning process. In fact, in Canada for instance, fire risk is traditionally managed after forest fires occur in areas under management. Fires generally trigger unpredicted changes in management and harvesting plans (salvage logging), specific equipment use (roads and machinery) and new timber supply analyses when timber losses are deemed consequential (Savage et al., 2010, for a recent review). When forest fires are taken into account during timber supply analyses, planned harvest targets are necessarily lower to prevent future deficits in harvestable volume (Armstrong, 2004; Didion et al., 2007; Savage et al., 2010). Since fire events are highly unpredictable, forest managers remain reluctant to reduce harvest targets beforehand, as it represents an immediate revenue loss. This a posteriori approach to accounting for fire can interfere with efforts to achieve sustainable forest management objectives and recently many authors have argued that fire risk should be integrated into forest management planning in a

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proactive way (Le Goff et al., 2009; Armstrong, 2004; Didion et al., 2007).

Usually, land classification (*sensu* Bettinger et al., 2009) is performed before timber supply analysis. The forest is subdivided into zones which are assigned specific or multiple forest functions, including protection of wildlife habitat, preservation of rare ecosystems or water resources, or timber production. Land can also be excluded from the timber production area for different reasons, including the natural absence of commercially valuable timber trees, steep slopes, inaccessibility or very poor growth. From an economic point of view, unproductive forests are excluded because they cannot produce a sufficient volume of trees of a minimum size in a reasonable period of time. However, areas assigned for timber production often include low- or marginally productive stands, namely when they are mixed with more productive stands. Such stands reach their minimum harvest age later than any other stand in the timber production area, hence they are more exposed to fire between two successive harvests (Bettinger et al., 2009). This increases the potential losses, since their harvest can be deferred because of fire. When most of the timber production area of a forest has a mean productivity well above the threshold limit that separates productive from unproductive stands, such losses may be regarded as negligible and ignored. However, beyond a certain proportion of marginally productive or vulnerable stands, action is required to minimize or at least to reduce potential fire losses.

In this paper, we explore a simple but proactive way of including risks and uncertainties in forest management planning through the identification of forest areas most vulnerable to fire because of their inherent productivity level. Using an eastern Canadian boreal case study, we propose different criteria to rationally exclude marginally productive stands, through (i) an analysis of forest productivity for different minimum harvesting thresholds and (ii) the analysis of two indicators of vulnerability to fire, namely the stand survival likelihood and the alternative rate of return of harvest operations. Finally, we describe how these indicators may help forest managers understand the implications of keeping or excluding marginally productive stands from the timber production area.

2. Methods

2.1. Study area

Our case study site, a forest management unit (FMU) 085-51 in the Canadian boreal forest, is located approximately between latitudes 48°50′N and 50°09′N and longitudes 78°05′ and 79°31′W (Fig. 1). This area belongs to the bioclimatic domain of balsam fir-white birch to the south (14%) and black spruce-feather mosses to the north (86%) (Robitaille and Saucier, 1998). With a total area of 10 830 km^2, wetlands (3480 km^2), unproductive (<50 m^3/ha within 150 years, Ministère des Ressources Naturelles et de la Faune du Québec – MRNFQ, 2003), inaccessible forest areas (820 km^2), water bodies (246 km^2) and protected areas (200 km^2) are excluded from the timber production area (5650 km^2) (Consultants DGR Inc., 2007). The annual allowable cut is 651 000 m^3 year^{-1} (equivalent to an annual production of 1.32 m^3/ha/year), mostly of black spruce (*Picea mariana* (Mill.) B.S.P. – 55%), jack pine (*Pinus banksiana* Lamb. – 26%), and trembling aspen (*Populus tremuloides* Michx. – 12%). The study area is in the Canadian Precambrian Shield and is mainly composed of volcanic, granite and gneiss material recovered by fine-textured lacustrine (38%), organic (poorly-drained sites – 24%), and glacial deposits (tills – 22%) (Bergeron et al., 1998). The topography is dominated by plains with an altitude around 280 m a.s.l. Glacio-lacustrine clay modified by the deglaciation process produced a particular deposit called the Cochrane till, a mix of clay and compacted gravel (Veillette, 1994; Légaré, 2009).

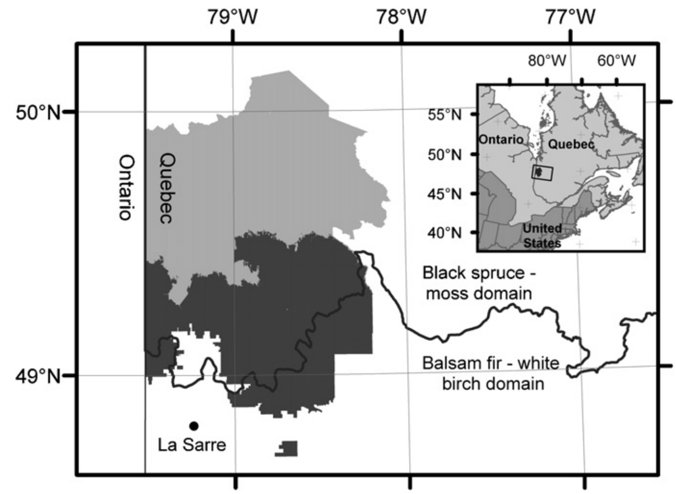

Fig. 1. Location and dominating forest vegetations of the study area. We considered in this study two forest zones: the high-productivity (dark grey) and the low-productivity (light grey) zones. Only black spruce – dominated stands were considered in our analyses.

This FMU can be divided into two forest zones based on their overall productivity; we will refer to them as the low-productivity and the high-productivity zones (Fig. 1). While distinct in terms of productivity, both forest zones are dominated by black spruce and are under a similar fire regime, so they are globally exposed to the same level of fire risk. Historical and current fire cycles (fire cycle: time required to burn an area equivalent to the study area, Johnson and Gutsell, 1994) were documented for the study area by Bergeron et al. (2004). Between 1850 and 1920, the fire cycle was estimated to be 135 years (95% confidence interval: 108–171 years), and the current fire cycle (1920–2000) is estimated to be around 398 years (302–527 years) (Légaré, 2009). Bergeron et al. (2006) estimated future fire rates based on the historical statistical relationship between annual area burned and climate conditions and on future climatic simulations from the CGCM1 (Flato et al., 2000) for 2040–2060 (2 × CO_2) – around 254 years, and for 2080–2100 (3 × CO_2) – around 79 years.

The northern part of this FMU is prone to paludification, a significant ecological process occurring in poorly drained sites dominated by black spruce in the Clay Belt (Simard et al., 2009). Paludification consists of soil organic matter accumulation accompanied with the rise of the water table leading to the progressive development of peatland (Payette and Rochefort, 2001). Therefore, this area is less productive and is constituted of more open forest (lowlands) interspersed with forested peatlands. In the southern part, the forests are denser and closed, and are also more productive.

The two forest zones are further subdivided into operating areas. Operating areas are used at the tactical planning scale for the purpose of distributing roads, harvesting activities (Andison, 2003) and the conservation of undisturbed forest (Belleau and Légaré, 2009). The study area includes 107 operating areas of a size between 30 and 150 km^2 which are relatively homogeneous in term of stand composition and delimited by physical limits, such as rivers or lakes (Annie Belleau, personal communications). We used these operating areas to compare the results at two planning scales, one that analyzed broad decisions over an entire forest over a long time horizon (strategic scale, one and a half the rotation age) and one that translated strategic decisions into feasible targets (tactical scale, one planning period) (Andison, 2003; Baskent and Keles, 2005).

2.2. Estimating the proportion of management zones that satisfy a minimum harvesting threshold, without considering fire

A minimum harvesting threshold is defined as a sufficient density of trees of a minimum size. In other words, it requires a minimum mean merchantable stem volume (dm^3/stem) and a minimum merchantable stand volume (m^3/ha). The merchantable volume of a stem corresponds to the volume with bark of the tree trunk up to a 9 cm diameter top (Perron, 1986). The stand volume is the product of the mean stem volume and the density of merchantable trees in a site. The minimum harvesting threshold is assumed at least to cover the cost of access, harvest, transportation, regeneration and management.

To cover the observed range of stand productivity in the entire area, we chose to contrast three harvesting thresholds: 50-50, 70-70, and 90-90 (dm^3/stem – m^3/ha). This range of thresholds is broad, as lumber value per stem doubles for black spruce stems of 50–90 dm^3 (Liu et al., 2007). The lowest harvesting threshold (50-50) is considered loosely constraining (MRNFQ, 2003), because a large proportion of forest stands will satisfy this harvesting threshold. The harvest of these stands however provides very narrow economic benefits. The highest harvesting threshold (90-90) brings greater economic benefits per unit area, but is very restrictive for this particular management unit, as it would exclude a very significant proportion of the actual timber production area.

A stand is excluded from the timber production area based on its potential to reach in one rotation the minimum harvesting threshold both at the stem and stand levels (MRNFQ, 2003; Bettinger et al., 2009). Yield tables developed by Pothier and Savard (1998) were used to identify productive stands (MRNFQ, 2003). These tables are based on site and relative density indices. Site index (SI) corresponds to the stand dominant height at a reference age of 50 years. It is a quantitative measure used to express tree growth potential of a forest stand (Alemdag, 1991) and remains independent of density for a wide range of tree densities. The relative density index is the ratio of observed stem density (total number of stems per ha) to a maximum stem density estimated for a given mean tree diameter with the self-thinning rule (Drew and Flewelling, 1979). With permanent sample plots, Pothier and Savard (1998) observed that relative density is sensitive to stand age, so they removed this age effect by referring to a relative density index at 100 years (RDI_{100}, their Eq. (11)). Although both indices are primarily intended to be applied to fully stocked and even-aged monospecific stands, they can also be used in irregular and more open stands (Monserud, 1984; Shaw and Long, 2007).

The minimum harvesting age, defined as the time required to reach the minimum harvesting threshold, was estimated for all black spruce stands of the study area with the yield tables of Pothier and Savard (1998). Site and relative density indices were estimated by the MRNFQ for the last timber supply analysis of the study area (2008–2013 planning period). Their methodology is briefly explained here. Stand polygons were delineated from a mosaic of aerial photos and grouped into management strata according to photo-interpreted information such as stand composition, age and density. Biometric characterization of the strata was based on approximately 8 inventory sample plots per stratum and located in stands with similar photointerpreted properties and within the constraint of the hierarchical ecological forest classification of Robitaille and Saucier (1998). Within each 400 m^2 inventory plot, species and diameter at breast height (dbh) of every tree with a diameter larger than 9 cm were recorded by 2 cm-dbh classes. Overall, 6148 sample plots were used. Saplings (diameter < 9 cm) taller than 1.3 m were counted by 2 cm-dbh classes in a 40-m^2 subplot. Height and age (ring count at 1 m) were measured on 2–5 sample trees per plot. In total, there were 755 management strata in the timber production area, out of which 747 included black spruce.

Median, skewness (a measure of the lack of symmetry in the data distribution) and kurtosis (a measure of peakedness of the data distribution when compared to a normal distribution) of the minimum harvesting age probability density function can be used as indicators of overall site productivity. A productive timber production area should have a low median minimum harvesting age, with its density function being strongly right-skewed and leptokurtic. We have examined these parameters both at the forest zone and operating area scales.

2.3. Probability to reach a minimum harvesting volume, considering fire activity

To estimate the probability that a stand escapes from fire and reaches the harvesting threshold, we used fire cycle lengths representative of the historical and future fire cycles reported for the study area (400, 200 and 100 years). We estimated the expected proportion of forest stands that will likely reach their minimum harvesting age without being affected by a forest fire. These results were compared with those obtained with a very low fire cycle (10 000 years), representing a situation where all fires would be suppressed or where almost no fire occurs.

To ease the interpretation of the assessment and to choose indicator thresholds below which a stand would be considered too vulnerable to fire risk, two vulnerability indicators were used at the stand level, one based on survival likelihood and another based on the alternative rate of return of harvesting activities. Assuming that in boreal forests fire activity is mostly controlled by weather (Parisien et al., 2011), the time-since-fire distribution (stand age distribution across the FMU) is negatively exponential (Johnson and Gutsell, 1994). The expected proportion of stands reaching a given minimum harvesting age is then given by:

$$p(A_{ht}) = \exp\left(-\frac{A_{ht}}{T_f}\right) \quad (1)$$

where A_{ht} is the age required for a stand to reach a minimum harvesting threshold and T_f is a fire cycle (years). Eq. (1) equals the survival likelihood of a specific stand for A_{ht} years in an area submitted to a particular fire cycle and may serve to assess stand vulnerability under a certain fire cycle. When the likelihood probability was below 66%, the stand was considered too vulnerable to fire to be included into the timber production area.

An indicator based on probability language, such as survival likelihood, may not be sufficiently informative to a forest manager. The action of classifying a stand as unproductive represents a potential profit loss, equivalent to abandoning the latent selling price that results from harvesting activities. The choice of including or excluding a stand into the timber production area can thus be equated to an investment decision in which two alternatives are assessed: keep or "sell" the stand to another use. We used the land expectation value (LEV) to represent the economical value of land with all harvesting benefits anticipated. LEV helps compare different projects or options. Usually, LEV is estimated at rotation start (Davis et al., 2001), but we compounded LEV to harvesting age in order to evaluate the first harvest decision and assumed that the stand would be "abandoned" to another use if the net profit of harvesting is less than the stand economical value. For stands at the harvesting threshold, the wood harvested will always have the same size and quantity as defined by the harvesting threshold, thus, costs and revenues can be expressed in units of merchantable volume. Also, one may further assume for simplification purposes that these operations take place simultaneously. Although untrue at the stand level (e.g. Klemperer, 1996), this is approximately valid at the forest scale. Under these assumptions, including a stand into the timber production area requires that:

$$LEV = V_h \frac{(1+i)^{A_h}}{(1+i)^{A_h}-1} \geq V_{ht} \tag{2}$$

where V_h is the volume (m^3/ha) expected to be harvested at the harvesting age (A_h), V_{ht} is the volume set by a minimum harvesting threshold and i is an interest rate. When LEV = V_{ht}, i corresponds to the minimum interest rate of return below which a decision maker would renounce harvesting activities in a given stand. We will further refer to it as the alternative rate of return (Davis et al., 2001).

The link between minimum profit and exposure is provided by the expected volume at harvest age, considering fire risk. As specified before, actual timber supply analyses are realized in a deterministic fashion and ignore the impact of fire hazard on timber harvest. As a consequence, stands whose productivity is at the limit of the harvesting threshold will be regularly scheduled for harvest, as any other productive stand will be. Should some of these stands burn before harvesting age, they will not be harvested at the scheduled time since their volume will always be below the minimum harvesting threshold. Consequently, the expected volume of a group of stands at the limit of the harvesting threshold V_h can be derived from the product of survival likelihood and volume at harvesting threshold:

$$V_h = V_{ht}\ \exp\left(-\frac{A_{ht}}{T_f}\right) \tag{3}$$

where A_{ht} is the minimum harvesting age. Eq. 3 may serve to replace V_h in Eq. (2) and Eq. (2) may be rearranged to isolate the alternative rate of return:

$$i_{ht} = \left(1-\exp\left(-\frac{A_{ht}}{T_f}\right)\right)^{-1/A_{ht}} - 1 \tag{4}$$

The alternative rate of return is a tool that serves to rate the profitability, in the present case, of harvesting activities. As expressed by Eq. (4), it can also be used as an indicator of profit exposure to fire risk. When looking at this indicator alone, we defined a stand as being vulnerable to fire when the alternative rate of return is below 2%.

An analysis of stand vulnerability combining both indicators should likely involve different values of alternative rate of return and survival likelihood. As the uncertainty of forecasted incomes increases with the length of the forecast, Moore et al. (2004) recommended using time-declining rates for cost-benefit analyses of public investment projects. They proposed 3.5% for intragenerational projects (less than 50 years), 2.5% for projects spanning 50–100 years and 1.5% for projects of 100–200 years. Using those time-declining rates, the alternative rate of interest will vary with the minimum harvesting age and correspondingly with the fire cycle (by Eq. (4)). Since the harvest age cannot be set analytically to the left of Eq. (4), the minimum harvest age for a particular fire cycle was estimated with a binary search algorithm using alternatively the three interest rates and assessing whether it fit within the length of the corresponding spanning time (Moore et al., 2004) for that interest rate. Once the interest rates and harvesting age were found (we used the lowest interest rates when there was more than one solution), survival likelihoods were then estimated with Eq. (1).

2.4. Vulnerability assessment at the management zone and operating area levels

In a first step, an analysis at the scale of forest management zones served to rate and to compare both indicators (survival likelihood and alternative rate of return). This analysis was not spatially explicit. Probability density functions of both indicators were used to assess the vulnerability of stands to fire. To help rate the overall vulnerability, survival likelihood probabilities were rated according to a scale presented by Patt and Schrag (2003). As an example, results will be presented using probabilities greater than 66% (i.e. stands will *likely* reach minimum harvesting age).

Table 1
Distribution (%) of the relative proportion of the timber production area by site (SI) classes and relative density indices (RDI_{100}) classes across the study area for the high-productivity and low-productivity forest zones. SI and RDI_{100} values correspond to central values of each class.

RDI_{100}	SI				
	9	12	15	18	21
High-productivity zone					
0.1	0.1				
0.3		4.5			
0.5		5.1	7.8		
0.7	0.2	18.6	55.6	7.7	0.4
Low-productivity zone					
0.1					
0.3		11.0			
0.5	7.2	36.6	9.6		
0.7		13.1	20.0	2.3	

Common ranges of interest rates for different project types were also used to evaluate values of alternative rates of return. A range between 2 and 4% is used for social discount rates for public investment (Moore et al., 2004), and interest rates higher than 4% may potentially attract private investors (e.g. Borders et al., 2008). A range between 4 and 8% is common for discount rates in temperate private forests (Borders et al., 2008; Klemperer, 1996) and discount rates higher than 8% are only used for highly productive plantations (Manley, 2007).

In a second step, the relative abundance of vulnerable stands by operating area was estimated. At this scale, vulnerability was rated by the frequency of vulnerable stands by fire cycle and minimum harvesting threshold because many management targets are defined in this way (e.g. biological refuges, residual forest, adapted silvicultural practices, etc.) (Belleau and Légaré, 2009). The abundance of vulnerable stands was described with an ACFOR scale: "Abundant" (more than 75% of the timber production area in a particular operating area), "Common" (50–75%), "Frequent" (25–50%) and "Occasional or Rare" (less than 25%).

In a third and last step, as vulnerable stands could be excluded from the timber production area, operating areas could themselves be excluded because of an insufficient proportion of timber production area relative to their total terrestrial area. The northern part of the FMU (the low-productivity zone) borders to the northern limit of commercial forest in Quebec and we used the minimum proportion of productive stands observed in the operating areas of the low-productivity zone (25%) as the threshold for excluding entire operating areas.

3. Results

3.1. Minimum harvesting thresholds and stand productivity

The differences in productivity at the zone level are reflected by the distribution reported in Table 1. More than 70% of the area is occupied by sites with SI above 15 and RDI_{100} above 0.5 in the high-productivity zone as compared to only 32% in the low-productivity zone.

The three minimum harvesting thresholds appear as segmented curvilinear curves or "hockey sticks" in a graph representing relative density index as a function of site index (Fig. 2). This curve form is caused by the double threshold definition, with a minimum

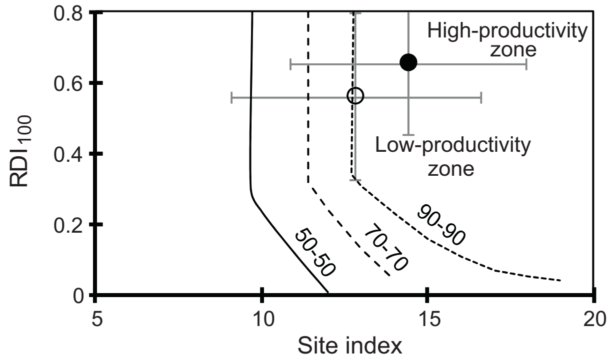

Fig. 2. Mean site index (SI) and mean relative density index (RDI_{100}) and associated 95% confidence intervals for the high-productivity (closed circle) and low-productivity (open circle) zones. "Hockey-stick" lines indicate the limit defining unproductive (left side) and productive (right side) stands for three minimum harvesting thresholds: 50 dm^3/tree and 50 m^3/ha (continuous line), 70 dm^3/tree and 70 m^3/ha (long dashed line), and 90 dm^3/tree and 90 m^3/ha (short dashed line).

achievable stem size that is insensitive to relative density index with the Pothier and Savard (1998) yield model (the hockey stick's shaft) and a minimum standing volume (the blade). Minimum stem sizes of 50, 70 and 90 dm^3 respectively correspond to site indices (SI) of 10, 11 and 13 m at 50 years. Stands to the right of the hockey stick are considered productive at the specified threshold level. This means that, without considering fire activity, close to 100% of the area in the high-productivity zone is considered productive under the 50-50 and 70-70 thresholds while it drops to 71% under the 90-90 threshold (Fig. 3). In contrast, in the low-productivity zone, 92% of the area is considered productive for the 50-50 and 70-70 harvesting thresholds and only 32% is considered as such for the 90-90 threshold.

At a 50-50 harvesting threshold, both zones have a low amount of unproductive sites. Under these conditions, the high-productivity forest zone is identified by a right-skewed and leptokurtic (i.e. with more acute peak than a normal distribution) density function (Fig. 3a), where the great majority of stands reach the threshold before 60 years. Conversely, the low-productivity zone presents a symmetric and almost mesokurtic (i.e. with a kurstosis comparable to that of a normal distribution) density function (Fig. 3a), where a majority of stands take less than 80 years to reach the threshold. When a higher threshold is considered (70-70), there is still a low amount of unproductive sites in both zones. The kurtosis becomes negative for both forest zones and skewness diminishes for the high-productivity zone (Fig. 3b). Finally at 90-90, there is an important increase in the amount of area that is considered unproductive at 27% and 67% for the high- and low-productivity zones respectively. For the productive portion, the density functions are truncated to the right, strongly left-skewed and leptokurtic while the majority of stands reach the minimum harvesting age in less than 80 years in both zones (Fig. 3c).

A finer analysis at the scale of operating areas shows a continuum of productivity situations but with a relatively clear distinction between the high- and low-productivity zones (Fig. 4). On average, when the minimum harvesting threshold is set to 50-50, operating areas of the high-productivity zone have a mean minimum harvesting age lower than 60 years and a skewness higher than one, while in the low-productivity zone these values are more than 60 years and less than zero (Fig. 4a and d). Similarly, the kurtosis values of the operating areas in the high-productivity zone are mostly greater than one, whereas they are mainly less than zero in the low-productivity zone (Fig. 4g). As was the case with the

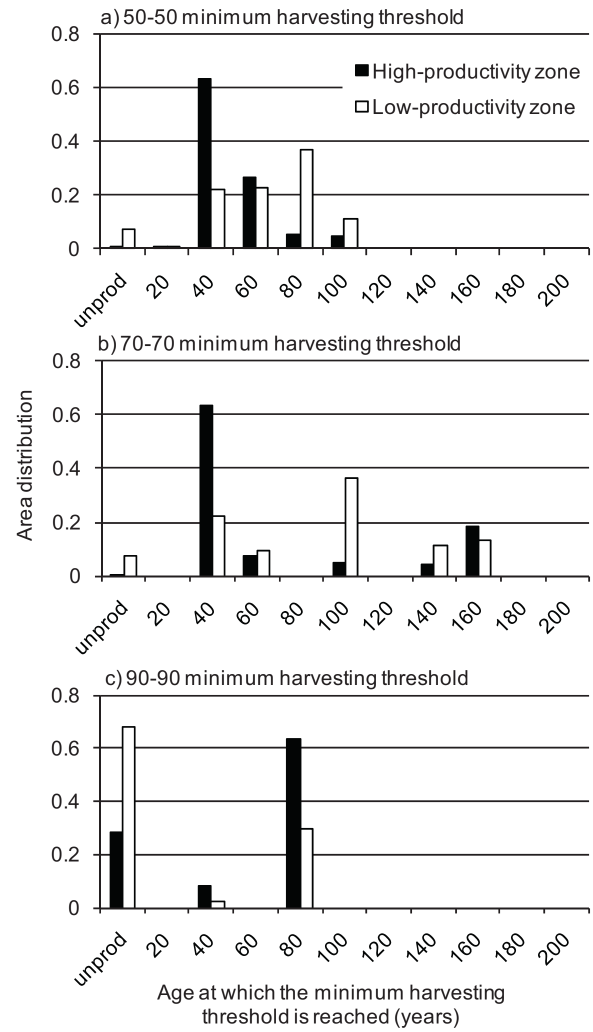

Fig. 3. Relative area distribution of the minimum stand age at which are reached different minimum harvesting thresholds (50-50: 50 dm^3/tree and 50 m^3/ha (a), 70-70: 70 dm^3/tree and 70 m^3/ha (b), and 90-90: 90 dm^3/tree and 90 m^3/ha (c)) for the high-productivity (closed bars) and the low-productivity (open bars) zones. "Unprod" indicates the proportion of the zones with SI and RDI_{100} too low to satisfy the corresponding minimum harvesting thresholds (see Fig. 2).

forest management zones (Fig. 3b and c), kurtosis of minimum harvesting age density functions by operating area becomes negative (Fig. 4h) and skewness diminishes (Fig. 4e) with a higher harvesting threshold (70-70). At the still higher harvesting threshold of 90-90, none of the operating areas of the low-productivity zone are excluded entirely, but have a median minimum harvesting age between 60 and 80 years. Kurtosis and skewness cannot be estimated anymore for some operating areas (Fig. 4f and i).

3.2. Vulnerability of forest productivity to fire risk: comparing both indicators

Stand level values of survival likelihood and alternative rate of return were computed with Eqs. (1) and (4) for different values of minimum harvesting age and fire cycles (Fig. 5). For the sake of presentation, first assume that if the survival likelihood probability is greater than 66%, stands will be considered as being productive enough to face the risk of fire. Stands would then need to reach the 50-50 threshold before 166 years under the current fire cycle (400 years) while harvest ages would have to be reached before 83 and

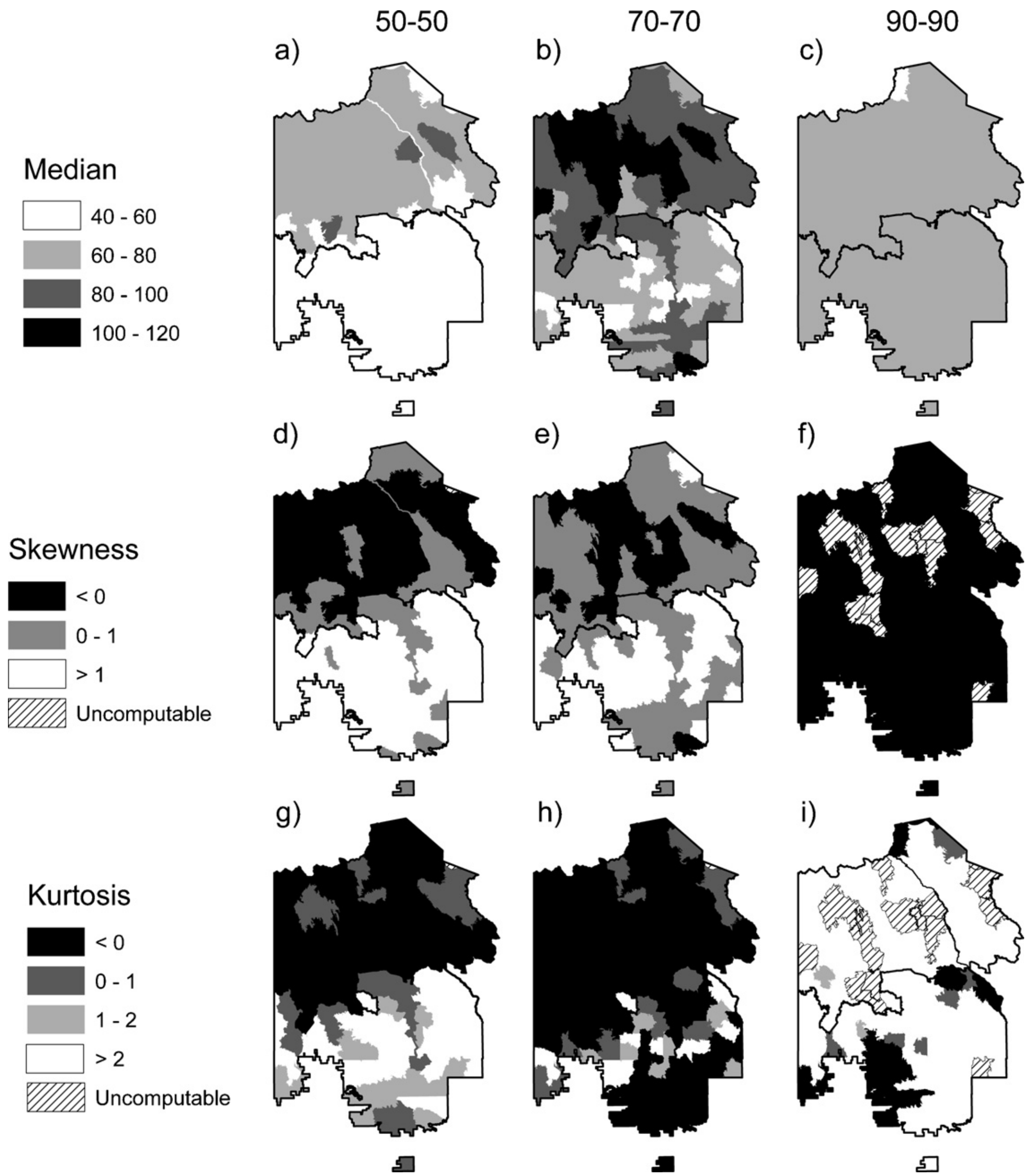

Fig. 4. Median (a–c), skewness (d–f) and kurtosis (g–i) of the density function of minimum harvesting age by operating area as a function of a minimum harvesting threshold (50-50: 50 dm^3/tree and 50 m^3/ha (a, d and g), 70-70: 70 dm^3/tree and 70 m^3/ha (b, e and h), 90-90: 90 dm^3/tree and 90 m^3/ha (c, f, i)).

41 years for 200- and 100-years fire cycles, respectively (Fig. 5a). In other words, to face an increasing fire risk (decreasing fire cycle), stands have to reach the harvesting threshold at a notably younger age, in a percentage equivalent to that of the fire cycle change (Eq. (1)). When the minimum alternative rate of return is set to 2%, for a fire cycle of 400 years, stands have to reach the 50-50 harvesting threshold before 84 years, a much lower value than the one set with a survival likelihood of 66% (166 years) (Fig. 5b). Under a 100-years fire cycle, the minimum harvest age required to achieve the rate of return target is approximately 49 years.

When comparisons are done at the scale of forest zones, with a 50-50 threshold, an increasing fire risk results in a faster decrease in the proportion of productive stands in the low-productivity zone (still assuming a minimum survival likelihood probability greater than 66% to face the risk of fire): from 88% (10 000 and 400 years fire cycle), 82% (200-years fire cycle) and 22% (100-years fire cycle) (Fig. 6d) as compared to 100%, 95% and 64% for the high-productivity zone (Fig. 6a). When our indicator is a minimum alternative rate of return of 2%, under a 400-years fire cycle, most of the stands of both forest zones are considered productive (Fig. 7a and d), but with an increased fire risk, however (200- and 100-years fire cycles), the proportion of timber production area decreases more rapidly in the low-productivity zone: from 45% (200-years fire cycle) to 22% (100-years fire cycle) (Fig. 7d) as compared to 90–64% for the high-productivity zone (Fig. 7a).

Proportions of area excluded from the timber production area are higher with more restrictive harvesting thresholds of 70-70 and 90-90 (Figs. 6b, c, e, f and 7b, c, e, f) but comparisons with both indicators set to 66% and 2% remain similar: a minimum survival

Table 2
Minimum survival probabilities resulting from considering fire cycle length, time-declining rates (from Moore et al., 2004) and minimum harvesting ages. Minimum harvesting ages are derived from Eq. (4) and minimum survival likelihoods from Eq. (1).

Fire cycle (years)	Minimum alternative rate of return (%)	Minimum harvesting age (years)	Minimum survival likelihood (%)
400	1.5	101	78
200	2.5	57	75
100	3.5	35	70

likelihood of 66% is approximately equivalent to an alternative rate of return of 2% for a fire cycle of 100 years.

To combine both indicators, combined harvesting ages, interest rates and survival likelihood for the three different fire cycles were defined. For a fire cycle of 400 years, we obtained a minimum harvesting age of 101 years and thus fixed the interest rate at 1.5%, in correspondence with projects spanning more than 100 years. The associated survival likelihood is 78%. Under a 200-years fire cycle, the minimum harvesting age (57 years) corresponded to a fixed rate of 2.5% (projects spanning 50–100 years), with a corresponding survival likelihood of 75%. Under a 100-years fire cycle, a rate of 3.5% (35-years minimum harvesting age) was assigned, with a corresponding survival likelihood of 70%. Hence, the use of time-declining interest rates of Moore et al. (2004) implies raising the minimum value of survival likelihood for longer fire cycles (Table 2).

3.3. Forest vulnerability to fire risk: operating area scale

The vulnerability of operating areas was assessed with the time-declining rates and minimum survival likelihoods of Table 2. Vulnerable stands are marginally productive stands rated too vulnerable to fire risk that should potentially be excluded from the timber production area. Consequently, some operating areas could themselves be excluded because of an insufficient proportion of timber production area. Without considering fire risk and with a minimum harvesting threshold of 50-50 or 70-70, a vast proportion of operating areas of both forest zones have more than 25% of their total terrestrial area included in the timber production area (Fig. 8a and b). With a 50-50 threshold under a 400-years fire cycle, although the proportion of productive stands in operating areas is slightly decreased (when compared to Fig. 8a and b), most of them still have more than 25% of timber production area (Fig. 8d). If the threshold for including or excluding operating areas is set at more than 25% of timber production area per operating area, then a major change is observed between the 70-70 and 90-90 minimum harvesting thresholds for the low-productivity zone (Fig. 8c). Major changes are also observed for the same zone with a 400-years fire cycle and a 70-70 threshold (Fig. 8e) or with a 200-years fire cycle and a 50-50 threshold (Fig. 8g). For the high-productivity zone, the exclusion of operating areas would only start to occur when considering a 200-years fire cycle (Fig. 8g–i), while a major shift is observed at 90-90 harvesting threshold (Fig. 8i).

Under the current fire cycle (400 years) and a 50-50 harvesting threshold, vulnerable stands are rare (1–25%) in most operating areas of the high-productivity zone, but somewhat more frequent (25–50%) in the low-productivity zone (Fig. 9a). With a 70-70 minimum threshold and a 400-years fire cycle, the majority of operating areas of the high-productivity zone have more than 25% of their area in vulnerable stands (Fig. 9b). In the low-productivity zone, almost all operating areas have more than 50% of their area in vulnerable stands for the same minimum threshold and fire cycle. For the 90-90 harvesting threshold, the vulnerability assessment radically changes between a 400- and a 200-years fire cycle for both forest zones (Fig. 9c and f).

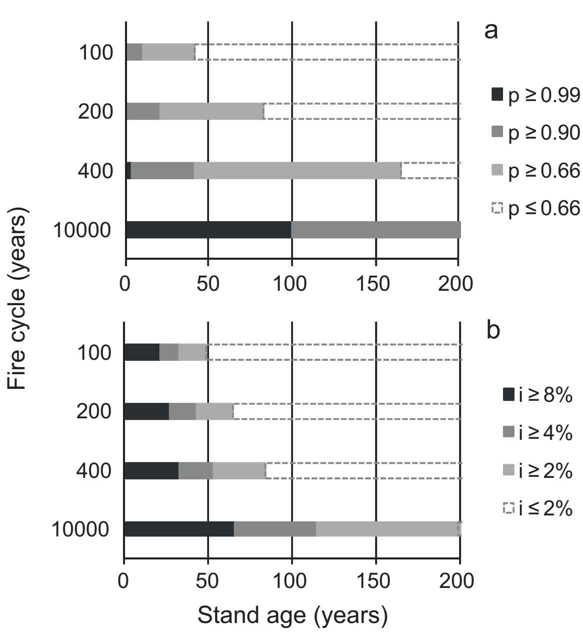

Fig. 5. Distribution of survival likelihood probabilities (a) and of alternative rates of return (b) as a function of the stand harvesting age for different fire cycles (Eqs. (1) and (4)).

4. Discussion

Fig. 8 illustrates the non-linearity of the relationship between the proportion of productive stands per operating area, the fire cycle, and the minimum harvesting threshold. In our case study, three different situations can be observed between which major changes occur in the proportion of the timber production area in operating areas: (1) Fig. 8a, b and d, (2) Fig. 8c, e, f, g and h and (3) Fig. 8i. In each of these three situations, the proportion of productive stands by operating area decreases gradually when considering fire risk or when the minimum harvesting threshold is increased. These results suggest that for a particular forest area under management, the identification of major break points may help forest managers to decide which minimum harvesting threshold is appropriate as a function of the productivity characteristics and fire cycle of the forests under management, as well as of the harvesting expectations placed on the forest being managed. Moreover, as fire disturbances are predicted to increase with the climatic change in many regions of the boreal forest (Flannigan et al., 2009; Bergeron et al., 2010), this approach also allows for assessment of vulnerablities that could be generated by such an increase.

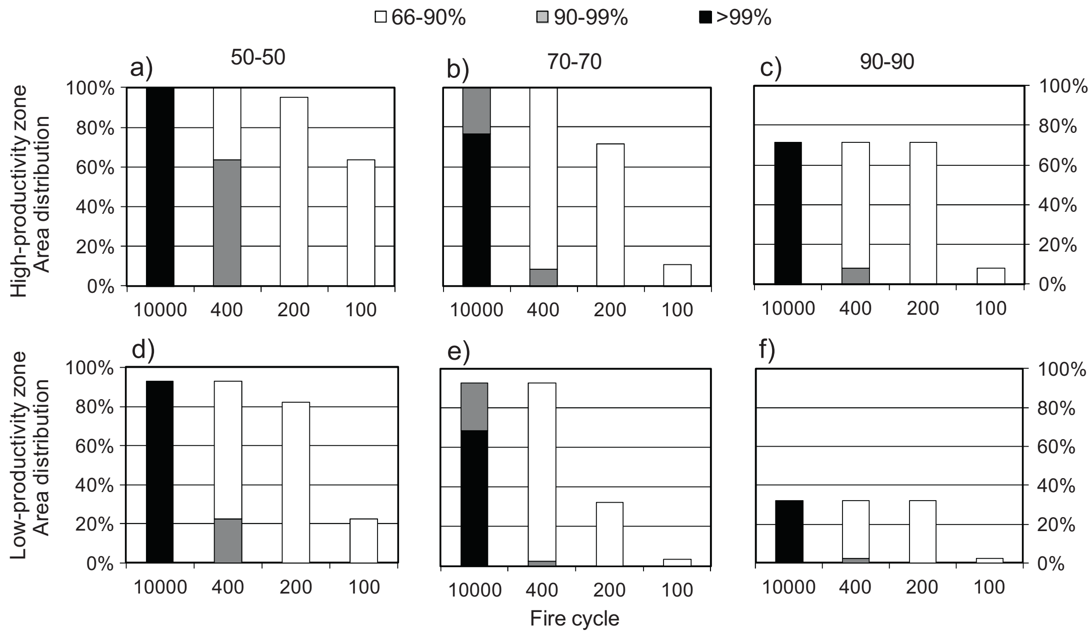

Fig. 6. Area distribution of the survival likelihood for four different fire cycles (10 000, 400, 200 and 100 years) and three different harvesting thresholds (50-50, 70-70 and 90-90) in the high-productivity (a–c) and low-productivity forest zones (d–f).

An alternative to excluding low-productivity stands vulnerable to fire would be to include the fire risk into the strategic planning phase. For a jack pine forest with a harvesting age of 65 years, Savage et al. (2010) recommended accounting for fire in a timber supply analysis when the burn rate is above 0.45% $year^{-1}$ (fire cycle below 222 years). This recommendation would hold for the high-productivity zone (Fig. 9a), as most of its timber production area has a minimum harvesting age below 70 years with a harvesting threshold of 50-50 (Fig. 3a) and, with a fire cycle of 200 years, vulnerable stands become frequent or common for most of its timber production area (Fig. 9d). For the low-productivity zone, however, approximately 47% of its timber production area has a minimum harvesting age higher than 70 years (Fig. 3a, 50-50) and 27% of its operating areas have frequent vulnerable stands when a fire cycle of 400 years is considered (Fig. 9a). Hence, the suggestion of Savage et al. (2010) should be gradated by forest productivity and production objectives. For instance, with a 70-70 minimum threshold and a 400-years fire cycle, 65% of the operating areas

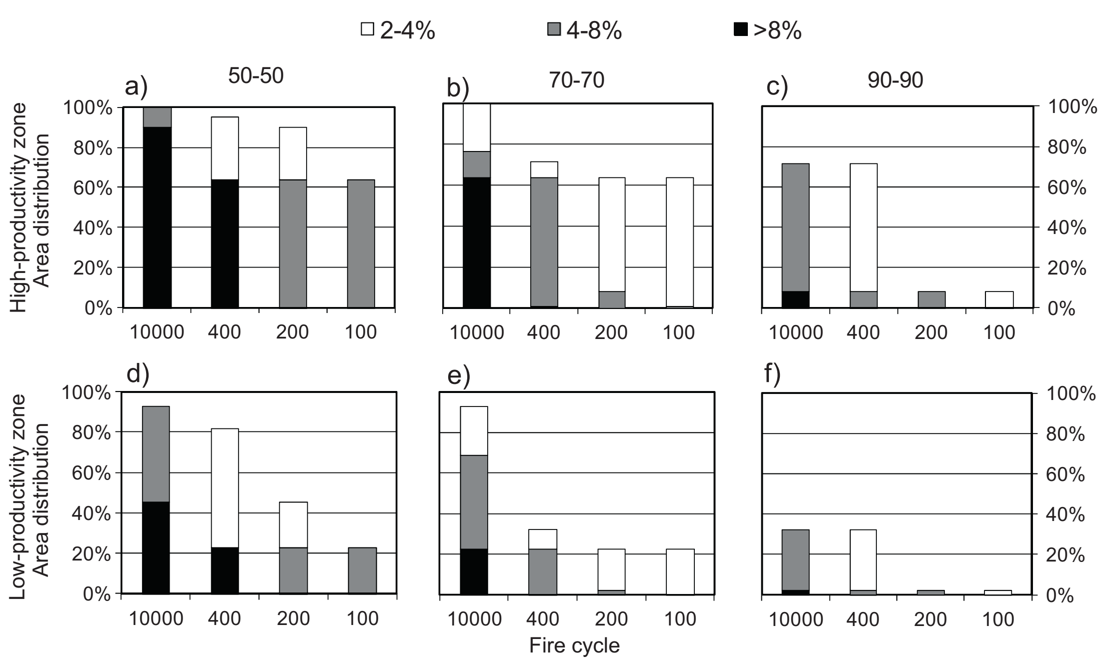

Fig. 7. Area distribution of the alternative rate of return for four different fire cycles (10 000, 400, 200 and 100 years) and three different harvesting thresholds (50-50, 70-70 and 90-90) in the high-productivity (a–c) and low-productivity forest zones (d–f).

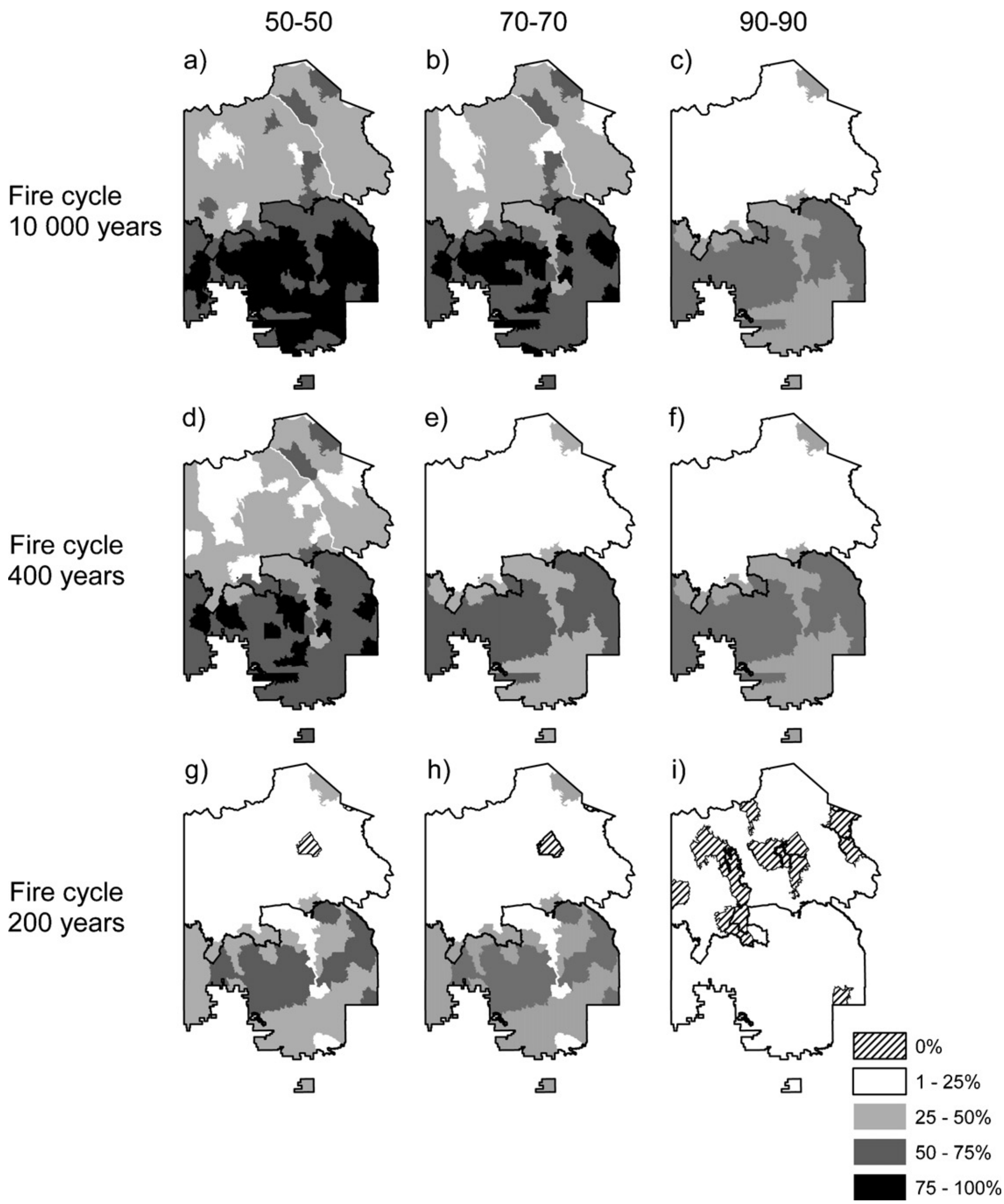

Fig. 8. Proportion of operating area considered productive under three different fire cycles. Productive stands are stands that reach the harvesting threshold under the required conditions defined by Table 2. Harvesting thresholds considered: 50-50 (left), 70-70 (center) and 90-90 (right).

of the high-productivity zone have frequent or common vulnerable stands (Fig. 9b), and, consequent to the present vulnerability assessment, fire risk should be accounted for in a timber supply analysis. Also, one could ask if a 70-70 minimum threshold should even be considered for the low-productivity zone (Fig. 9b and e). Only the most productive stands of both zones can sustain a 90-90 minimum threshold (Fig. 3c) and the vulnerability assessment radically changes between a 400- and a 200-years fire cycle (Fig. 9c and f).

The present approach of excluding low-productivity stands vulnerable to fire could also be seen as complementary to the inclusion of fire risk during the strategic planning phase. Indeed, most of the studies that accounted for fire risk in timber supply planning (except Peter and Nelson, 2005) made the simplifying assumption that their studied forest had only one single age-volume relationship (e.g. Van Wagner, 1983; Reed and Errico, 1986; Armstrong, 2004; Savage et al., 2010) or a single harvesting age (Didion et al., 2007). Accounting for stand vulnerability to fire resulting from the time necessary to reach harvest eligibility can be seen as a strategy to reduce the risk of future harvest deficits, while also permitting a lower reduction of current harvestable volume. One should be careful, however, not to cause biodiversity problems by concentrating harvesting activities in the most productive sites (Paquette and Messier, 2011).

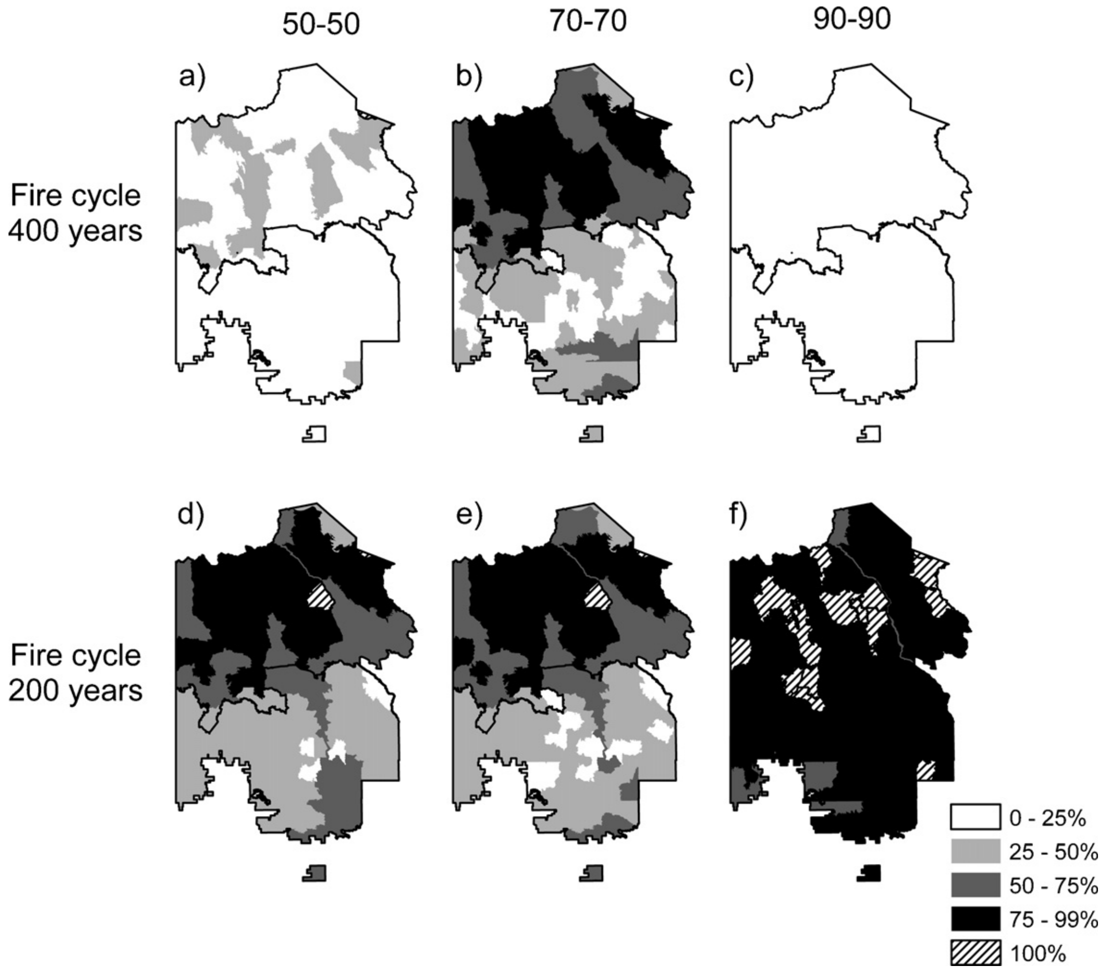

Fig. 9. Proportion of vulnerable stands by operating areas for 400-yr (a–c) and 200-yr (d–f) fire cycles. Vulnerable stands are stands that do not reach the harvesting threshold under the conditions defined in Table 2. Harvesting thresholds considered: 50-50 (left), 70-70 (center) and 90-90 (right).

5. Conclusions

The survival likelihood probability and the alternative rate of return may be used to estimate the vulnerability of marginally productive stands to forest fire risk. We developed, presented and illustrated how these indicators allow forest managers to decide the appropriate minimum harvesting threshold when implementing a harvest strategy on a particular area as a function of productivity characteristics, fire activity (current or future) and certainty of desired outcomes. The assessment of timber vulnerability to fire is sensitive to the considered fire cycle and production objectives.

The approach developed and demonstrated with our case study is applicable to other regions where fire is a dominant type of disturbance, provided that the time to reach an harvesting threshold and a fire risk can both be assessed. It has the advantage of being less complex to undertake than a complete timber supply analysis while allowing to make an analysis over an entire forest management unit in order to decide on production targets while considering fire risk. The analysis of forest vulnerability to fire proposed in this study needs to remain framed within the concepts of sustainable forest management to avoid potential biodiversity problems in the most productive sites.

Finally, the proportion of stands vulnerable to fire may serve to decide whether or not including fire risk into strategic planning. Such a decision, that necessarily implies a lower planned harvest level, could be weighted against the potential economic loss of excluding vulnerable stands from the timber harvest area. The identification of major break points in the vulnerability assessment may help to decide which minimum harvesting threshold is appropriate as a function of the productivity characteristics and fire cycle of the forest under management.

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