Simulation of historical and current fire regimes in central Saskatchewan for annual allowable cut determination

Chao Li*, Canadian Forest Service, Edmonton, AB, Canada
Hugh Barclay, Canadian Forest Service, Victoria, BC, Canada
Jianwei Liu, Manitoba Conservation, Winnipeg, MB, Canada
Doug Campbell, Saskatchewan Environment, Prince Albert, SK, Canada
Greg Carlson, Manitoba Conservation, Winnipeg, MB, Canada

*Corresponding author:
Chao Li, Canadian Forest Service, 5320 – 122 Street, Edmonton, AB, Canada T6H 3S5; Tel: (780) 435-7240; Fax: (780) 435-7359; E-mail: cli@nrcan.gc.ca

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Abstract:
The dynamics of Canadian boreal forests are affected by the catastrophic natural disturbance regimes such as forest fire. Therefore, the determination of annual allowable cut (AAC) needs to take this factor into account, especially under the climate change scenario that predicted significant increase of fire activities. To achieve this goal, a model that can simulate fire regimes under different fire management effort is necessary. We adapted the Spatially Explicit Model for DANdscape Dynamics (SEM-LAND) to the Saskatchewan conditions and performed a model experiment to simulate the fire regimes in a study area located in the central Saskatchewan. The simulation results suggest that fire suppression could lead to longer fire cycles, smaller mean fire sizes, more fire numbers per year, and increased mean forest age (time since fire). The relationship between mean forest age and annual area burned was estimated from the results of this model experiment. This relationship can be used to determine the ideal fire management target of annual allowable area burned from expected future forest conditions.

Keywords: fire regime, SEM-LAND model, Saskatchewan, fire suppression simulation, fire management

1. Introduction
The ultimate goal of contemporary forest land management is to achieve sustainable resource development and to maintain biodiversity for the benefit of current and future generations. Fire management is a critical component in forest land management in Canada because fire has played a significant role in shaping Canada’s forest landscapes, especially in the boreal region (Weber and Flannigan, 1997). Numerous studies have revealed that many boreal tree species have adapted to environments with frequent fires and that fire behaves differently in different forest types (e.g., Chandler et al., 1983).
Therefore, a reasonable deduction is that natural fire regimes are the result of interactions among vegetation, fire events, and environmental conditions such as weather. If this deduction is true, then fire management decisions can alter the course of a fire regime compared to natural conditions. Consequently, understanding how the ecosystem components interact to produce observed fire regimes and forest dynamics is crucial to the design of future fire management practices. This understanding has unfortunately not been fully developed. This study is attempted to provide insight on this understanding from a modeling perspective.

Under the paradigm of the adaptive resource management, the determination of annual allowable cut (AAC) needs to consider the influence of fire and other disturbance regimes. Projected climate change scenarios could also influence the determination of AAC through the changes in forest growth rate and disturbance regimes. All of these presented a challenge for resource managers, especially for the regions suffering frequent and irregular catastrophic disturbances such as our study area - a forest landscape in central Saskatchewan with a size of 132,886 ha. This paper presents our results so far in an ongoing case study of developing the capability of simulating fire regimes under different levels of fire management operations. This appears to be the first step in adjusting the AAC accordingly to adapt and mitigate climate change impacts and achieve sustainable development.

Landscape-disturbance models provide a useful approach for synthesizing and integrating existing information from different research fields, as well as incorporating available data sets of landscape structure and environmental conditions. The simulation results from these models can provide another set of “data” that represents the logical consequences of available knowledge obtained from the stand-scale studies. Landscape disturbance models can also serve as analytical tools to evaluate the effects of different forest- and fire-management options under current and future environmental conditions. The Spatially Explicit Model for LANdscapes Dynamics (SEM-LAND) is one such landscape-disturbance model designed to capture the major characteristics of forest landscape dynamics (Li, 2000; Li and Barclay, 2001).

2. Materials and methods

2.1. The SEM-LAND model

The raster-based SEM-LAND model simulates a forest landscape as a grid of rectangular cells. For each cell, we assumed a homogeneous cover type, species composition, and age or time since last fire. The simulation of forest fires was based on predictions from the Canadian Forest Fire Weather Index system (Van Wagner, 1987); and the Canadian Forest Fire Behavior Prediction system (Forestry Canada Fire Danger Group, 1992). We used 1-ha spatial resolution in the model. The model can output results at a yearly time step.

The SEM-LAND model has three main components: forest growth, fire disturbance, and forest regrowth after fire. Forest growth was simulated as the volume and age increment since the last fire. A two-stage fire disturbance process was simulated, consisting of fire initiation and fire spread (Li and Apps, 1995, 1996). “Fire initiation” starts from the
presence of an ignition source and proceeds until most trees within the cell are burned. Once a cell is burned, fire has the potential to spread to adjacent cells. “Fire spread” continues until it is stopped in all directions.

The basic equations for simulating the probability of fire initiation \( P_{\text{Initiation}} \) and fire spread \( P_{\text{Spread}} \) are given by the following equations:

\[
P_{\text{Initiation}} = P_{\text{BaseInitiate}} \times F_{\text{FuelWeather}}
\]

\[
P_{\text{Spread}} = \begin{cases} 
0 & (R \geq R_{\text{Crit}}) \\
(P_{\text{BaseSpread}} \times F_{\text{FuelWeather}} \times F_{\text{Slope}} \times (1 - FSE)) & (R < R_{\text{Crit}}, S < S_{\text{Crit}}) \\
(P_{\text{BaseSpread}} \times F_{\text{FuelWeather}} \times F_{\text{Slope}}) & (R < R_{\text{Crit}}, S \geq S_{\text{Crit}})
\end{cases}
\]

where \( P_{\text{BaseInitiate}} \) and \( P_{\text{BaseSpread}} \) are the baseline fire probabilities for the initiation and spread stages; \( F_{\text{FuelWeather}} \) is scale factor calculated according to the Canadian FBP system representing the influence of fuel type and weather conditions; \( F_{\text{Slope}} \) is the scale factor due to slope; \( R \) is the daily precipitation; \( R_{\text{Crit}} \) is the critical value of daily precipitation, and any precipitation that reaches or exceeds that value can stop a fire; \( FSE \) is the fire suppression efficiency; \( S_{\text{Crit}} \) is the critical value of fire size, and any fire that reaches or exceeds that size can escape from fire suppression; the baseline fire probabilities for the initiation and spread stages are characterized by the equation:

\[
P_{\text{Base}} = k / [1 + \exp(a - b \times Age)]
\]

where \( a, b, \) and \( k \) are parameters, and \( Age \) is the forest stand age or time since last burn. Detailed formulas for calculating the scale factors \( F_{\text{FuelWeather}} \) and \( F_{\text{Slope}} \) can be found in Li (2000). The SEM-LAND model would be applicable to the Saskatchewan conditions, if the simulation results can reconstruct fire regimes with and without fire suppression compared to the estimated fire cycles from the available fire history records.

### 2.2. Fire suppression simulation

In the revised SEM-LAND model used in this study, a lightning initiated fire subject to fire suppression efforts is simulated in three stages. Stage 1 starts when a lightning strike ignites a fire at a given site, and runs until it has been detected, reported, and fire crews arrive on the scene. The growth of a free-burning fire simulated during stage 1 is similar to the AIRPRO model. Stage 2 runs from the beginning of the initial attack until the fire has been stopped by management operations, or the fire has escaped from the fire suppression effort. Fire suppression efforts reduce the probability of fire spread during this stage. Stage 3 is the continuation of the second situation (escape of the fire) and runs until the fire is finally stopped. In Stage 3, fire growth is simulated as if it is unconstrained again (similar to Stage 1). This three-stage fire suppression description is not intended to capture every detail of ground fire-suppression operations, but is a
scheme that could be used in the fire regime simulators to investigate possible long-term consequences of fire suppression on the dynamics of fire regimes and forest ecosystems.

This three-stage fire suppression was simulated in the SEM-LAND model by combined user-defined scenarios of fire suppression efficiency and of the critical fire size of fires that can escape from suppression. The fire suppression efficiency was expressed by a reduced probability of fire spread due to fire suppression, which reflects the level of protection executed by the fire suppression agencies. The level of protection can be represented by the resource investment to the operation and the equipment and facilities used in the operations. The critical size of fire that can escape from suppression indicates a starting point when the probability of fire spread would return to a level that represents natural conditions.

2.3. Study area
The Fort A La Corne study area, total size 132,886 ha, is a forest landscape surrounded by agricultural lands located in central Saskatchewan (Figure 1). This area falls entirely within the Boreal Transition Ecoregion, which represents the gradation from the grasslands of the south to the boreal forest of the north. The common tree species are jack pine (Pinus banksiana Lamb), trembling aspen (Populus tremuloides Michx.), and black spruce (Picea mariana (Mill.) B. S. P.). The area is particularly susceptible to fire due to the light rainfall, lack of moisture retaining soils, abundant dry fuels, and the fuel debris preserved by the dry conditions. Since 1943, most fires in the area have been relatively small except for three: the Steep Hill fire of 1967 burned 13,700 ha; the Henderson fire of 1989 burned 11,100 ha; and the English fire of 1995 burned 28,500 ha.

Fig. 1. Location of the study area in central Saskatchewan, Canada.

In the model, current forest conditions in the area were represented by geographic information system (GIS) data layers such as the forest cover type, stand age, and tree density at 1-ha resolution (Fig. 2a, c, and d).
Fig. 2. Maps of the Fort A La Corne study area, Saskatchewan: (a) original land cover type; (b) reconstructed land cover type; (c) current forest age; and (d) crown closure.

The forest age distribution was determined by using the FRAGSTATS software package (McGarigal and Marks, 1995). A time-since-fire distribution was constructed from the forest age distribution according to Johnson (1992) following a methodology review (Li, 2002). This data was used to determine whether the fire regime had changed in the past.

Forest inventory records were not available for about 40% of the total area of the study site, because several large fires had occurred in 1995. To provide this missing data, a map of provincial fuel types was placed over the forest cover type layer, and the corresponding forest cover types were converted for those pixels with missing data, providing the reconstructed forest cover map required for the model simulations (Fig. 2b). For these pixels, we set the stand age for the burned area to zero, and tree densities to intermediate level of crown closure class (50-75%) before the burns.

Li (2002) showed that stand-origin map-based estimation of fire cycles can overestimate the length of fire cycle. This could be particularly exaggerated in area burned recently by large fires. Therefore, the stand-origin map of the study area portion that was not burned by the large fires in 1995 was used for the fire cycle estimate.
2.4. Model experiment

We conducted a model experiment aimed at exploring possible dynamics of fire and the forest landscape with and without the influence of fire management. The $FSE$ can be defined from 0 (indicating no effect at all) to 1 (indicating total success of fire suppression). The $S_{C_{rit}}$ varies in each individual fires due to a variety of causes such as the level of investment (person hour) provided for a given fire, accessibility of the scene, technology and equipment used by the fire management agency, and weather conditions. For a given region, however, a distribution could be built based on the records of fire suppression operations in the past, and the mean value of the distribution could be the $S_{C_{rit}}$ estimate. In this model experiment, the fire suppression scenario was simulated with a 50% reduction of fire spread probability ($FSE = 0.5$) and the critical burn size, $S_{C_{rit}}$, was defined as 20, 50, and 100 ha, which might be corresponding to different mean fire sizes under different fire suppression efforts. The scenario without fire suppression was simulated for $FSE$ of 0 and the $S_{C_{rit}}$ was set to 1 ha. In each scenario, 10 replications were conducted to obtain the range of variability in simulated fire and forest dynamics.

The simulation results were summarized for fire cycle, mean fire size, fire number, and mean forest age. The fire cycle ($FC$) was calculated by the equation:

$$FC = \sum_{i=1}^{n} \frac{BA_i}{(TA \times n)} \quad [4]$$

where $BA_i$ is the area burned in the $i^{th}$ year, $TA$ is the size of the total area under investigation, and $n$ is the total number of years.

The SEM-LAND model was written in FORTRAN 77, and the model experiment was run on a Sun Blade 2000 computer under the Solaris operating system. Each of simulation runs took various CPU time ranging from 10 to 20 hours depending on the length of fire cycle.

3. Results

3.1. Calibration of the model

We calibrated the model by comparing observed and simulated fire cycles under natural conditions. The observed fire cycle was based on the time-since-fire distribution calculated from the current forest age mosaic pattern (Fig. 3). The time-since-fire distribution analysis indicated that the fire cycle changed around 1945. Before 1945, the fire cycle was about 105 years (76.5% of area burned), and after 1945 the fire cycle was about 213 years (23.5% of area burned). Very few studies referred to the reasons of such fire regime changes, and one suspected reason was that the study area is surrounded by agricultural land that was expanded during the period. Although a detailed fire history study for the area, such as that Weir et al. (2000) did for the Prince Albert National Park, could provide a better estimate of fire cycles, the estimates obtained from existing forest
inventory data can serve as an approximation before such a fire history study is performed. These fire cycles were used to calibrate the SEM-LAND model.

A small study area (9462 ha) within the Fort A La Corne study area was randomly selected to perform the model calibration. The model was calibrated according to the fire cycle before 1945 by adjusting the overall fire probability across the landscape. The simulated fire cycle for this small area was calculated as about 104 years under natural conditions for a 1000-year period. The calibrated model was then used to explore the fire regimes under natural and current conditions for the whole study area.

3.2. Simulated fire regimes

3.2.1. Fire cycle

The simulated fire cycle for the whole study area under natural conditions was about 104 years (range, from 82 to 114 years Fig. 4a), which is close to the 105 years demonstrated in the empirical data.

Under the fire suppression scenario, the simulated fire cycles were longer than under natural conditions. When the fire suppression efficiency was fixed at 0.5, the simulated fire cycles increased with the increasing critical fire size of escaping from suppression. When the critical fire size of escaping from suppression was set at 100 ha, for example, the fire cycle was 211 years (range, from 157 to 269 years). This result was consistent with the observed fire cycle of 213 years for the study area.
Fig. 4. Simulated mean value (and standard deviation) under different fire management scenarios expressed as size of escaping fire. The 1-ha class represents the natural condition without fire suppression. The size classes of 20, 50, and 100 ha indicate different fire suppression efforts when fire suppression efficiency was set at 50% reduction of probability of fire spread. Results of four indicators from our simulation experiment are shown: (a) fire cycle; (b) mean fire size; (c) fire number per year; and (d) mean forest age.

3.2.2. Mean fire size
Our simulation results indicated that the mean fire size decreased from about 168 ha (range, 150 to 224 ha) under natural conditions to 78 ha (range, 59 to 103 ha) when the $S_{Crit}$ was set at 100 ha (Figure 4b).

3.2.3. Fire number per year
Our simulation results showed that the mean fire number per year has been increased under fire suppression scenario (Figure 4c). A standard one-way ANOVA analysis (Venables and Ripley, 2002) was performed to determine if the annual fire numbers are significantly different among various fire suppression scenarios. The ANOVA (Table 1) indicated that differences in annual fire numbers are highly significant under different fire suppression efforts ($p$-value $= 0.46 \times 10^{-10}$).
Table 1. ANOVA analysis for the annual number of fires under different fire suppression scenarios.

<table>
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<th></th>
<th>Df</th>
<th>Sum of Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(F)</th>
</tr>
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<td>2.536777</td>
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<td>4.6119e-011</td>
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<td>36</td>
<td>2.481122</td>
<td>0.068920</td>
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</tr>
</tbody>
</table>

3.2.4. Mean forest age
Our simulation results indicate that the average stand age (time since last burn) across the landscape can increase under fire suppression scenarios. Under natural conditions, fires burn frequently, resulting in a mean stand age of 38 years. With increasing fire suppression, the mean stand age increases to 77 years when the critical fire of size that can escape from suppression is defined as 100 ha (Figure 4d). The standard deviation about the mean stand age also increases from 5.3 (without fire suppression) to 12.9 (with fire suppression when the critical fire size of escaping from suppression defined as 100 ha).

4. Discussion
4.1. Simulation modeling approach
The SEM-LAND model was developed to reconstruct natural fire regimes in west-central Alberta, Canada (Li 2000). Our results indicate that the SEM-LAND model can be adapted to simulate the forest conditions of central Saskatchewan for reconstructing the natural fire regimes in the region. This model capability was developed from the process-based model structure and means that other modules can be added to address other issues. The fire suppression simulation module described in this article is an example of how the improved model can be used to evaluate the long-term effects of fire suppression policy on forest and fire dynamics.

Landscape-scenario fire models have been used to investigate the landscape consequences of different fire regimes. For example, Baker (1995) showed the differences in landscape dynamics under fire regimes before and after European settlement through a simulation experiment carried out by the DISPATCH model. Baker (1995) demonstrated that the fire size distributions obtained from empirical data of the two periods were different: there were large numbers of small and intermediate fires and fewer large fires before European settlement and increased small fires and reduced numbers of intermediate and large fires after European settlement (corresponding to conditions close to fire suppression). Using these two fire size distributions as model input, the DISPATCH model was able to simulate the landscape consequences of the two different fire regimes. A similar approach can be implemented in any of the landscape-scenario fire models such as SELES (Fall and Fall, 2001), LAMOS (Lavorel et al., 2000), and LANDIS (Mladenoff and He, 1999).

Fire suppression is a fire management measure aimed at reducing the final size of burned forest areas. Some earlier fire management models simulated detailed ground fire suppression activities. For example, the AIRPRO model for air tanker operations (Simard and Young, 1978) simulated the growth of free-burning fire up to the start of fire
suppression, then simulated the perimeter growth of a fire during suppression, air tanker utilization, and final fire size when the fire was successfully suppressed. Mop-up and patrol after the fire were also simulated in the AIRPRO model.

Fire suppression simulation in the SEM-LAND model differs from the method used in landscape-scenario fire models. The difference is the process-based modeling approach used: fire size distribution does not need to be defined before the simulation is carried out. Instead, fire size distribution is the model output and thus can be compared with empirical observations. The fire suppression simulation module we developed was based on the general knowledge of initial attack operations in fire management practice (e.g., Simard and Young, 1978). This process-based modeling approach allowed interactions among different modules to generate the dynamics of both forest and fire across the landscape. The algorithm for simulating fire suppression might be difficult to implement in landscape-scenario fire models because fire sizes are predetermined by sampling from a defined fire-size distribution, thus no change in fire size can be made during a simulation.

4.2. Simulated fire regimes
The simulated fire cycles demonstrate that fire suppression can alter the fire cycle under certain combinations of fire suppression efficiency and critical fire size of escaping from suppression. Since empirical data are not currently available to compare the reduction of probability of fire spread, the results from this simulation experiment can serve only as theoretical support for the assumption that fire suppression increases the length of the fire cycle. Nevertheless, our results were consistent with the fire cycles observed in different fire management zones. For example, Ward et al. (2001) recalculated fire cycles based on the methodology suggested by Miyanishi and Johnson (2001) and found that during the past 40 years, the annual area burned was 1.11% in the area without fire suppression (about a 90-year fire cycle) and 0.34% in the area with fire suppression (about a 294-year fire cycle).

Because the fire cycle lengthened under fire suppression conditions, the mean fire size was expected to decrease if the fire number per year was kept unchanged. Our simulation results support this expectation. An increase in the mean number of fires per year under fire suppression scenario was a surprise result. We were expecting minimal difference in the number of fires because the model experiment was designed to use the same time series of fire ignition source as model input. The significant difference in mean fire number per year suggests that the chance of a fire spreading is higher after a history of fire suppression in the forest. Fire suppression allows a higher proportion of the forest to grow to more flammable older stages (see equation 3 and section 3.2.4), so that fire probability becomes higher.

4.3. Management applications
Emulating natural fire patterns in harvest planning is one of the paradigms in contemporary forest management. Implementing this forestry policy requires a good understanding of both natural and human-influenced fire regimes. Ideally, this understanding would be achieved through gathering empirical data, followed by a
thorough statistical analysis. Because such empirical data is scarce, we used a process-based modeling approach to reconstruct natural fire regimes from information on current forest conditions. Our simulation results suggest that fire suppression can lead to changes in fire cycle length, fire size, and mean fire number per year. The longer fire cycles and smaller fire sizes under fire suppression scenarios are interrelated theoretically, assuming there is no significant change in number of fire per year (Li et al., 1999). Figure 5 shows the predicted trend in fire cycles under different combinations of mean fire size and fire number per year for the study area, based on equation [4]. Smaller fires lead to fewer annual burns, and a longer period is required to burn an area equal to the whole landscape. This theoretical prediction can be seen as a “neutral” model for comparison with empirical observations or simulation results.

Fig. 5. Theoretical predictions of fire cycles under different combinations of fire number per year and mean fire size.

This theoretical correlation between mean fire size and fire cycle could actually be nonlinear because of changes in fire number per year under different fire suppression scenarios. Increased effort in fire suppression could allow forests to grow older, thus increasing the probability of fire. Consequently, an increased number of fire sources could eventually develop into fire initiations. In our simulation, fire probabilities were assumed to increase with forest age until about 30 years old and then to reach the maximum value. This treatment implicitly assumed that a fire could sustain itself in forests close to or older than 30 years old. This assumption was based on reported observations and opinions from a number of fire researchers in Canada (e.g., Mike Flaningan, Canadian Forest Service, pers. comm.). Further discussion on the role of fire
suppression is beyond the scope of this article. Our focus here is to explore the potential management applications of our results.

As mentioned, fire suppression could allow forests to grow older, and the forest resource availability across the landscape could then be increased. Based on our simulations, for example, mean forest age might double when the suppression effort reaches a level such that the critical fire size of escaping suppression is 100 ha with a fire suppression efficiency of 50% reduction of fire-spread probability. Although a further fire-suppression policy analysis is impossible due to the shortage of empirical data evaluating the savings through fire suppression, our results are still useful because of the confirmation of the common assumption that fire suppression alters natural fire regimes (e.g., Miyanishi and Johnson 2001; Ward et al. 2001).

One of the central issues in fire management research is determining the optimal level of fire management or suppression. From an economic perspective, the optimal level should be established by comparing suppression related costs and the value saved by the suppression action (e.g., Martell, 1978). Other factors, such as human injury and private property lost, social-economic development of local communities, environmental impact, and the natural benefits of fire, will also need to be taken into account. The level of protection model was developed to meet needs in different regions of Ontario (Martell and Boychuk, 1997). The crucial challenge of this economic approach lies in the difficulties involved in evaluating the value saved as a result of the suppression actions.

Our modeling tools could be used in forest resource management planning. The optimal level of fire management or suppression could be determined from the optimum mean forest age (equivalent to the area weighted age in forest management in raster-based model simulations) that could keep the forests at the most valuable stage including both timber and non-timber values. Under this approach, the goal could be to determine the fire management target from an expected future forest condition, or to use fire suppression as a management tool to achieve the goals of forest resource management. The optimum forest age would differ by region. The focus here is to establish the relationship between the most favorable mean forest age and the annual area burned that needs to be maintained as a fire management goal. In fact, this annual area burned should include all the areas of stand-replacement disturbances such as areas harvested and destroyed by pests, etc. Figure 6 shows this relationship based on our simulation results: the older the expected mean forest age, the higher the fire suppression effort must be.

The relationship between expected mean forest age and the annual area burned can also be calculated from the negative exponential probability distribution where the reciprocal of the only parameter of the distribution is equal to the mean forest age or fire cycle (Van Wagner, 1978). However, the calculated AAC represents an optimistic viewpoint of resource availability that would allow stand-replacement effect happen in much larger area annually (about 2.7 times) than that estimated from spatially explicit model simulations. The simulation results recommend conservative estimate of resource availability due to the unstable forest landscape dynamics.
Fig. 6. The relationship between expected mean forest age and the annual burned area that must be maintained through fire management.

The relationship shown in Figure 6 has a direct management application for the study area at Fort A La Corne. For instance, it would be difficult to maintain a mean forest age older than 50 years if the annual burned area exceeds 973 ha. Therefore, if the expected forest age were no less than 50 years, then the target goal for fire management would be to control the annual burned area below 973 ha. This prediction may or may not be easy to achieve in practice. For example, about 40% of the total area was burned in 1995, which is more than 50 times higher than the expected annual threshold, an extremely large area burned in a single year needs to be compensated for by a long period when the annual burned area does not exceed 973 ha. If a higher mean forest age were planned for, the difficulty would become even greater, and require a higher investment in fire suppression operations. Due to the stochastic or semi-stochastic nature of fire disturbance process, such scenarios may have to be taken into account in forest resource management decision-making.

The methodology we have developed can be applied to other forest regions, but the relationship presented in Figure 6a would differ according to landscape conditions such as forest and vegetation cover. A more thorough evaluation of fire suppression policy would require a more detailed operational-level fire model to evaluate both timber and non-timber values saved through fire suppression operations.

References


