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# Assessing the impact of stand-level harvests on the flammability of forest landscapes

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**Abstract.** The harvesting of forest stands can reduce landscape flammability by fragmenting fuel continuity in ways that make it difficult for fires to spread and by providing firefighters with fuel discontinuities they can use as anchor points for suppression operations. We describe a methodology for assessing the impact of harvesting designated forest stands on landscape flammability and expected losses. We combine assessments of the probability that fires will be ignited at any point on the landscape with probabilistic predictions concerning how long escaped fires will burn and how they will spread. Shortest path methods are used to identify critical paths that link potential ignition points with values at risk. We then rank stands with respect to their ability to disrupt those critical paths and thereby reduce landscape flammability and fire losses. We describe how we applied our methodology to a 12 964-ha forested area of boreal forest in the province of Alberta, Canada. Our results indicate that the crucial stands in our study area, those that have the most significant impact on landscape flammability and fire loss, tend to be those that are flammable and located on or close to critical paths that link areas where fires are most likely to occur with values at risk.

**Additional keywords:** fire–smart forest management, fire spread, fuel management, shortest path algorithm.

## Introduction

Although fire is a natural process that has beneficial impacts on many natural forest ecosystem processes, it also poses threats to public safety, property and other forest values. Fire and forest managers therefore develop and administer fire management programs that are designed to achieve an appropriate balance between the many potential detrimental and beneficial impacts of fire and the cost of implementing such programs.

Fuel management is the explicit manipulation of forest vegetation to achieve fire management objectives. It may involve the establishment and maintenance of fuel breaks that may slow or stop the spread of fires or serve as anchor points for fire suppression operations and the conversion of some forest stands to less flammable vegetation.[1] It can also include the reduction of surface fuels, decrease of crown density, thinning, and the use of prescribed fire (Agee and Skinner 2005). The use of fuel breaks has been shown to have a positive effect by reducing the size and intensity of fires over short temporal and small spatial scales (van Wagtendonk 1996; Finney 2001; Bevers *et al*. 2004; Loehle 2004), and across long temporal and large landscape-level scales (Finney *et al*. 2006). The conversion of some areas to deciduous species with lower fire spread rates has also been shown to be effective at reducing the burn probability (Parisien *et al*. 2006).

Forest managers typically view fire management (including fuel management) as an exogenous activity that can produce reductions in burned area that contribute to enhanced industrial forest productivity. The effect of exogenous reductions in the average annual burn fraction on the annual allowable cut (AAC) of a forest has, for example, been studied using timber harvest scheduling models (e.g. Martell 1994) that can be used to assess how fire management or the level of fire protection

[1] We use the term 'landscape flammability' to describe the extent to which a forest landscape is susceptible to burning. In that context, an increased probability of fires occurring or growing larger would render a landscape more flammable. The online version of the Oxford English Dictionary (http://dictionary.oed.com/, accessed 30 May 2007) defines 'inflammable' as 'capable of being inflamed or set on fire; susceptible of combustion; easily set on fire'. The Oxford Dictionary of Current English (Thompson 1998) notes that '*flammable* is often used because *inflammable* can be mistaken for a negative (the true negative being *non-flammable*).'

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influences timber production. However, the timing and location of harvesting operations themselves can influence fire spread and landscape flammability and their potential impact on fire loss should be assessed endogenously.

Integrated approaches to fuel and forest management (which Hirsch *et al*. (2001) refer to as fire-smart forest management) address the fuel management implications of harvesting and silviculture at the same time as they address traditional timber production objectives. The premise of fire-smart forest management is that timber harvest scheduling and other land management activities (e.g. road construction) can alter forest fuel complexes in ways that contribute to decreases in the number and size of escaped fires and areas burned. Such reductions in the flammability of the forest landscape can augment the value of existing fire management programs that produce a reduction in burned area (which forest managers treat as an exogenous variable) with an enhanced secondary reduction in burned area above and beyond the primary reduction that results from the fire management program itself. Put simply, the harvesting and regeneration of a forest stand may reduce the flammability of the landscape and future forest-level fire losses, and thereby contribute to a secondary increase in the AAC.

Some authors have investigated the impact of forest management practices on fire behaviour. Harvesting, for example, has been shown to reduce fire spread across a landscape and its spatial location appears to be a key factor that contributes to reductions in the risk of large fires (Johnson *et al*. 1998; Gustafson *et al*. 2004; Gonzalez *et al*. 2005). Similarly, thinning as well as other fuel management practices have been shown to be effective in reducing fire hazard (Stephens 1998; Graham *et al*. 1999; Pollet and Omi 2002).

Finney (2005) addressed the importance of incorporating the probability of fire occurrence, fire behaviour, and values at risk (to which we would add fire suppression effectiveness) in strategic or long-term fire management planning, but the development of spatial fire risk assessment procedures, the importance of which was so well articulated by Sampson and Sampson (2005), who reminded us that 'all wildland areas share wildfire risks with their surroundings', has yet to receive the attention it deserves.

We have developed a methodology for assessing what we define as the Fire Protection Value (FPV) of a forest stand, the extent to which harvesting that stand would afford protection to all the stands on the landscape. Our methodology considers fire ignition, fire spread, and fire suppression effectives as well as values at risk. We now describe our methodology, how we applied it to a 12 964-ha area of boreal forest in the province of Alberta, and the results we obtained.

## Methods

### Overview

We began by partitioning the forest landscape into a large number of small cells. Our approach (which is illustrated in Fig. 1) integrated two models – a Fire Model that predicted where fires might ignite and how they might spread across the landscape, and a Fire Protection Model that predicted the impact of cutting a stand on the expected fire loss incurred on the landscape. The Fire Model provided cell-to-cell fire spread estimates to the Fire Protection Value (FPV) Model, which identified the many

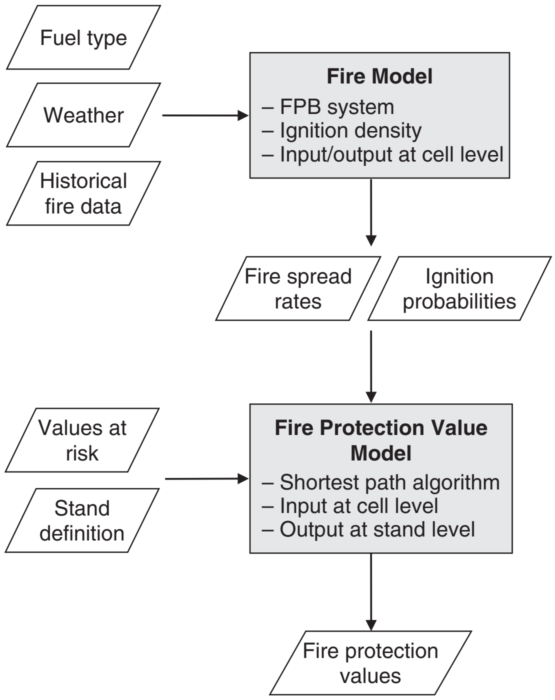


**Fig. 1.** Schematic diagram of our Fire Protection Value methodology. Rectangles represent the components of the approach and parallelograms represent data, intermediate-derived information and output data.

routes fire could use to travel between all pairs of cells on the landscape. Given the location of the values at risk (timber volume in our case) and the harvest block definition (grouping of cells with similar vegetation structure and silviculture regime into patches that can be harvested), our model determined what we refer to as the FPV of a harvest block, the marginal contribution that harvesting that block would make to the value of the forest by slowing fire spread across the landscape and reducing losses were it to be harvested. The FPV of a harvest block was therefore the reduction in the expected loss of the values at risk on the landscape if that harvest block was harvested. Our estimate of the FPV was based on an assumption that when a block is harvested, all the fire paths that use that block (i.e. those that pass through one or more of the cells in that block) will be interrupted and 'forced' to use alternative, possibly slower paths.

### Study area

We applied our methods to a 16.6 × 12.6-km (20 790-ha) subset of Millar Western Forest Products Ltd's Forest Management Agreement area (FMA #97–0034) near the community of Whitecourt in central-west Alberta, Canada. Millar Western's FMA falls within the Foothills and Boreal Forest natural regions of Alberta (Natural Regions Committee 2006). The total forested area in our 20 790 ha study area was 12 964 ha and the rest of our study area was classed as roads, rivers, lakes, urban communities and other non-flammable cover types.

Millar Western's 1997–2006 Detailed Forest Management Plan describes the 1961–1998 fire activity observed in a 3.7 million-ha area (53°8′–55°5′N and 114°–117°W) in which our study area was embedded. A total of 4695 fires or an average of 124 fires per year were observed and 90.8% of them burned less than 10 ha, but the annual area burned ranged from as little as 34 ha to as much as 265 757 ha during that period. A total of 61% of the fires were human-caused and the remaining 39% were lightning-caused. Lightning- and human-caused fires each burned roughly 50% of the area burned.

The study area was divided into a regular grid of 23 000 cells (30 × 30 m or 0.09 ha each) and a digital map coverage of the forested area was used to display a cover type map that we used to subjectively aggregate the forested cells into 464 harvest blocks. The harvest blocks were homogeneous with respect to forest cover type and age class and ranged from 13 to 46 ha and averaged 27.9 ha in size.

### Fire Model

In order to assess the FPV of harvest blocks, we first modelled fire ignition and spread processes so we could predict where fires might ignite and how they might spread. Our landscape was partitioned into a large number of cells and as it is reasonable to assume the probability distribution of the number of fires that occur in a cell each day is Poisson (see, for example, Cunningham and Martell 1973), it is reasonable to assume the probability distribution of the number of fires that occur in each cell each year is Poisson with a mean that varies from cell to cell. Historical fire records were used to estimate average annual fire occurrence rates in each cell.

We used the Canadian Forest Fire Behaviour Prediction (FBP) system (Forestry Canada Fire Danger Group 1992) to model fire behaviour. The FBP system is a set of empirical models that can be used to predict fire spread rate, fuel consumption and fire intensity as functions of fuel type and weather expressed in terms of the Canadian Forest Fire Weather Index System (FWI) codes and indices (Van Wagner and Pickett 1987). It includes fuel models that are used to classify forest types into 17 fuel types that collectively represent most of the major forest cover types in Canada.

As we were only concerned with the spread of large fires that escape initial attack, we used fire behaviour parameters that are representative of extreme fire weather conditions, the fire weather associated with the 10 worst days (expressed in terms of the FWI) observed at the Windfall fire weather station in the Millar Western FMA study area during the period 1989–1999. Note that although this choice was somewhat arbitrary, our objective was to assess changes in landscape flammability before and after specified stands had been harvested, so the set of fire weather conditions used would not significantly influence our results as long as they were severe enough to support active fire spread. Fire spread depends on vegetation or fuel, weather and topography, and we used FBP spread rates to predict the rate of spread from every cell in which a fire can burn to all of its adjacent cells.

### The Fire Protection Value Model

The FPV model predicts how the harvest of a harvest block will influence fire spread across the landscape. Consider a forest landscape that has been partitioned into $n$ cells. An ordered pair of cells is a pair of cells, the first of which is designated as the origin of a fire and the second of which is a cell to which that fire can spread. There are $n \times (n-1)$ ordered pairs in an $n$-cell landscape. The ordered pair $(i, j)$ denotes a fire that can start in cell $i$ and travel to cell $j$ whereas the ordered pair $(j, i)$ refers to a fire that can start in cell $j$ and spread to cell $i$. We refer to the paths that link two cells as directed paths because the time required for a fire to spread from cell $i$ to cell $j$ may well vary significantly from the time required for a fire to spread from cell $j$ to cell $i$, because the forest landscape is anisotropic with respect to fire spread owing to wind and topography. There may, of course, be many directed paths between the two points in a directed pair, but a fire will always follow the shortest (with respect to time) path to travel from the cell in which it starts to a cell to which it is travelling. We defined a *valid* pair of cells as any directed pair of cells for which there was a non-zero probability that a fire would ignite the source cell and that fire could spread to the destination cell.

Our FPV model identified the many routes that fire could use to travel between all valid pairs of cells and assumed that when a block was harvested, any fires that passed through cells in that block would be forced to use alternative (possibly longer) paths. As there are many paths that fire could use to travel between any two points, the interruption in fire spread that results from harvesting a block may not stop the fire but rather force it to burn across or follow a less flammable or slower route and thereby slow its advance. The primary impact of harvesting a block will be to eliminate the possibility that the timber growing in that block can burn in the future, but the blocks with the highest protection values will be those that belong to 'preferred' or critical fire paths that link high fire occurrence cells to high value timber areas.

Finney (2005) proposed and discussed a quantitative definition of fire risk that includes both fire behaviour probabilities and fire effects. His definition is formulated as a change in the expected net value (summed losses and benefits) caused by all fire behaviours and all possible values. In a similar but slightly simplified way, we defined $\mathrm{FI}(i, j)$ as the potential impact of fire in cell $i$ on values at risk in cell $j$, as follows:

$$\mathrm{FI}(i, j) = P_i \times V_j \times PL_{ij} \quad (1)$$

where $P_i$ is the probability that a fire ignites in cell $i$, $V_j$ is the timber volume or some other value at risk due to fire (to be protected) in cell $j$ and $PL_{ij}$ is the probability that a fire that ignited in cell $i$ will reach cell $j$. We used the commercial timber volume here, but other values such as public safety, property and ecological impacts (both positive and negative) can also be considered. We also assumed that value $V_j$, which is lost when cell $j$ is burned is independent of the fire's intensity, which is reasonable given the fact that we modelled only the spread of high intensity (and therefore very destructive) fires.

Recall that we used a set of fire behaviour parameters that are representative of extreme fire weather conditions. Although this choice was arbitrary, our objective was to assess changes in landscape flammability before and after specified stands have been harvested and the set of weather conditions used would not significantly influence our results as long as they were high enough to support active fire spread. Our approach is a variant of what Finney (2005) describes as a model simplification 'short cut', which has been used by others including Roloff *et al.* (2005).

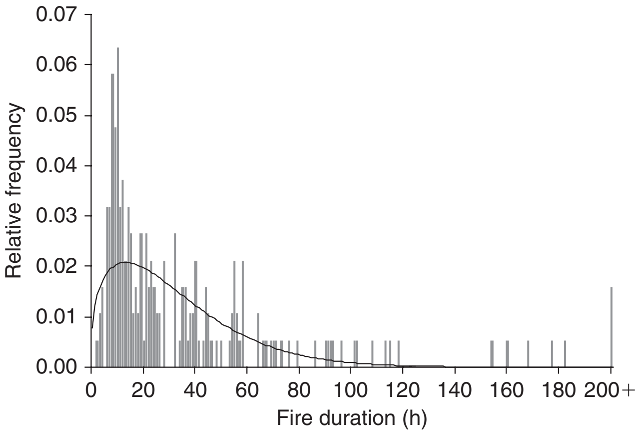


**Fig. 2.** Relative frequency and Weibull probability distribution function of the time fires that burn 100 ha or more burn freely. (Based on wildfire statistics provided by Sustainable Resources Development, Government of Alberta.)

We defined $PL_{ij}$ as the probability that a fire that starts in cell $i$ burns long enough to travel over the entire length of path $L_{ij}$. We first determined $L_{ij}$, the time required for a fire to travel from cell $i$ to $j$. We then used the probability distribution function of fire duration to estimate the probability the fire would last long enough for the fire to traverse that path. Most fires that occur in the province of Alberta are contained by the initial attack force and the time they burn out of control is not indicative of the time large escaped fires might burn across the landscape. We therefore focussed on the small percentage of fires that escape initial attack and burn 100 ha or more to model the time escaped fires burn out of control.

To estimate the parameters of the probability distribution function of fire duration, we used the fire report data for the Alberta fires that occurred during the years 1983 through 1995 and burned 100 ha or more. We fitted a Weibull function (Eqn 2 with $\alpha = 1.4$, $\beta = 25.9$ and $x$, a given value of the fire duration random variable $X$) to the time those fires burned freely.

$$f(x; \alpha, \beta) = \frac{\alpha}{\beta^{\alpha}} \times x^{(a-1)} \times e^{-(x/\beta)^{a}} \qquad (2)$$

The frequency distribution of the time (h) such fires burned freely and the fitted distribution are illustrated in Fig. 2.

The simplest method of estimating $L_{ij}$, the time a fire requires to travel from cell $i$ to cell $j$, would be to use the spread rates between adjacent cells and a shortest path algorithm to identify the shortest path between $i$ and $j$ as Kourtz *et al.* (1977) and Finney (2002) did. Let F($x$) denote the probability distribution function of fire duration, the probability that the fire duration is less than or equal to $x$. Then $PL_{ij}$ is the probability that any fire burns longer than $L_{ij}$, that is, $P(X > L_{ij}) = 1 - P(X \leq L_{ij}) = 1 - F(L_{ij})$.

We considered two scenarios to assess the potential impact of harvesting block k and thereby preventing fires from spreading through it. We first determined the shortest path between cell $i$ and cell $j$. If this path does not pass through any cell in block k, then harvesting block k will have no effect on the spread of a fire between cells $i$ and $j$ and harvesting block k will contribute no protection value for this pair of cells. If the shortest path from cell $i$ to cell $j$ passes through at least one cell in block k, then harvesting block k may have an impact on the spread of fire from cell $i$ to cell $j$ because a fire that starts in cell $i$ may have to traverse a longer path to reach cell $j$ if it cannot burn through block k. Note however, that the shortest path between any two cells may not always be unique. If there is at least one shortest path that does not pass through block k, the time required for a fire to traverse the shortest path will remain the same and harvesting block k will have no effect on the spread of the fire from cell $i$ to cell $j$.

The next step was to determine $L_{ij}$(k), the fire's shortest path from cell $i$ to cell $j$ (expressed in terms of hours) if all the cells in block k had been harvested. If the post-harvest fuels are less flammable than the fuels that occupied block k before the harvest (i.e. they support slower spread rates), then $L_{ij}$(k) will be greater than or equal to $L_{ij}$. Consequently, $PL_{ij}$(k), the probability that the fire will reach cell $j$ after block k has been harvested will be less than or equal to $PL_{ij}$, the probability that the fire will reach cell $j$ if block k is not harvested. We could then use $L_{ij}$ and $L_{ij}$(k) to calculate $PL_{ij}$ and $PL_{ij}$(k), the probabilities that the fire will travel from cell $i$ to $j$ with and without block k, respectively. We then defined $FP_{ij}$(k) as the fire protection of block k with respect to the directed cell pair $(i, j)$, the marginal difference in the fire effect of cell $i$ on cell $j$ with and without block k.

$$\mathrm{FP}_{ij}(\mathrm{k}) = P_i \times V_j \times (PL_{ij} - PL_{ij}(\mathrm{k})) \qquad (3)$$

This procedure accounts for the fact that there is usually more than one path between $i$ and $j$ and if block k belongs to a particular path, harvesting it will not stop the spread of the fire from cell $i$ to cell $j$, but it will simply force the fire to follow another, possibly slower, path. We repeated this process for all valid pairs of cells $(i, j)$, that is, for any fire starting in any cell $i$ that can spread to any other cell $j$ on the landscape.

Let VP denote the set of all valid pairs of cells $(i, j)$, and FPV(k) the total Fire Protection Value of block k. FPV(k) was obtained by summing the protection values associated with all the fire paths between all valid pairs $(i, j)$ that pass through block k, that is:

$$\mathrm{FPV}(\mathrm{k}) = \sum_{(i,j)\in \mathrm{VP}} \mathrm{FP}_{ij}(\mathrm{k}) \qquad (4)$$

Note that we assessed FPV(k) by considering the effect of harvesting block k in isolation from all the other blocks on the landscape. There may be some interaction when more than one block is harvested, that is, block k may have a different FPV if a neighbouring block k′ is also harvested. The net effect of harvesting such blocks would therefore not be the sum of FPV(k) and FPV(k′). We address this issue in our Discussion.

### *Software implementation of the FPV model*

Landscapes with large numbers of cells lead to very large number of pairs $(i, j)$ for which fire paths must be evaluated. As noted earlier, if fire can travel from any cell to all other cells on a landscape, the number of directed pairs of cells in the set of valid directed pairs of cells would be $n \times (n - 1)$ for a landscape with $n$ cells. In order to apply this model to the 231 000 cells in which the study area is partitioned, we would have needed to carry out a very large number of arithmetic operations, even when using an efficient shortest path algorithm. We therefore explored how we might improve the computational performance of our model by implementing the following approximating measures:

(i) We did not consider all pairs of cells $(i, j)$ to compute the shortest paths, but only those for cell $j$ that was not 'too far' from ignition cell $i$. A fire may not be able to travel from any particular cell $i$ to all other cells to which it is linked with flammable paths because the duration of the fire may be less than the time required to traverse those paths. We therefore limited our analysis to cells that can be reached within 65 h (the 90th percentile of the fire duration distribution) because fires are not likely to reach cells that are more than 65 h away.

(ii) We explored the impact of aggregating cells into $m^2$ cell multicellular units (MCUs), assuming some spatial auto-correlation in fire behaviour at the cell level. Each MCU was then assigned the average spread rate of its cells and the sum of the volume of their cells. This reduced the spatial resolution of our study area and the time required to solve the problem by a factor of $m^2$ because fewer cells were analysed.

(iii) We did not consider all shortest paths computed to evaluate the FPV of a block. Paths between pairs of cells located too far away from a block k will not be affected by its harvest.

To compute the FPVs, we considered each cell $i$ and identified all the cells $j$ that were within the defined maximum travel time (see point (i) above) and their associated fire travel time $L_{ij}$. Clearly, a suitable shortest path algorithm had to be used, such as Dijkstra's using heaps (Ahuja *et al.* 1993). The time required to carry out this step was constant for each cell $i$ and it was independent of the total number of cells, as we only needed to consider cell $i$'s neighbourhood. Once we had identified the set of cells considered to be in the neighbourhood of cell $i$ we could identify the set of blocks that might influence the spread of fires that started in cell $i$ (see point (iii)).

When block k is harvested, the travel time from cell $i$ to other cells may change and must therefore be recomputed. For each block k in cell $i$'s neighbourhood, we computed the times $L_{ij}(\mathrm{k})$, assuming block k had been harvested, to all cells $j$ within the maximum propagation time considered (point (i)). For every cell $j$, we compared $L_{ij}(\mathrm{k})$ and the time assuming that the block k had not been harvested, $L_{ij}$. FPV(k) was then updated by adding the value $P_i \times V_j \times (PL_{ij} - PL_{ij}(\mathrm{k}))$.

Our last simplification was to group individual cells into larger MCUs as described in point (ii) above. In the graphical representation of the study area, cells were arranged in a regular raster grid structure. We noticed, however, that adjacent cells were generally similar to each other at the scale ($30 \times 30$ m) we used. We tested this assumption by comparing the FPVs using all 231 000 cells (complete resolution) with the FPVs obtained after grouping cells into 4, 9, ..., 100-aggregate MCUs of $m^2$ cells ($m = 2$–$10$). This aggregation strategy evaluates regularly distributed subsets (of size $n\,m^{-2}$) of cells and, as a result, the FPVs were reduced by approximately the same factor, $m^2$. Our assumption was that it was reasonable for us to do so because we were concerned primarily with the relative rather than the absolute magnitude of the FPVs, and harvest blocks with the highest or lowest FPVs in the original high resolution coverage would retain their highest or lowest FPVs in the lower resolution aggregate instances. Although some information could be missing in this aggregation, high correlation coefficients (0.99) for all values of $m$ indicated that this strategy produced almost the same relative FPVs as those obtained using the original high-resolution coverage.

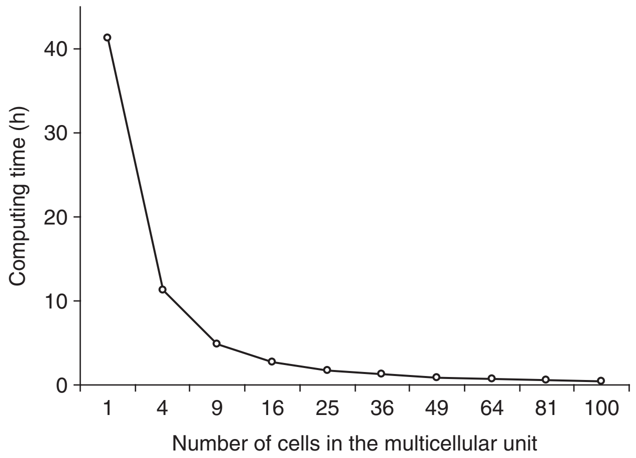


**Fig. 3.** Reduction in computing time produced by aggregating individual cells into multicellular units.

Computing times were drastically reduced by using this aggregation strategy (Fig. 3). Using a Pentium IV-1.2 GHz with 512 Mb RAM and a forest containing 231 000 cells and 464 harvest blocks, execution time decreased from 41.3 h without cell aggregation to less than 26 min for 100 cell MCUs ($m = 10$). Fig. 3 also shows that the cell aggregation strategy reduced computation time by a factor close to $m^2$. Given the trade-off between decreasing the size of the problem and preserving solution quality, 100-cell aggregations were therefore adequate for our purposes.

### *Analysis*

We analysed the main characteristics defining the FPV of a harvest block, as detailed in our Discussion section below. The total FPV of a block was used to explore the effect of block size, and FPV per unit area was used to analyse the effect of other variables like block location, cover type and fire ignition. We also carried out a neighbourhood analysis to investigate the relationship between the FPV of a harvest block and the timber volume in the surrounding area.

## Results

The FPVs of the harvest blocks are shown in Fig. 4*a*, where darker colours indicate higher fire protection values. Larger blocks tended to have higher FPVs. The largest 20th percentile of the harvest blocks (the 5th quintile) contained close to 31% of the total fire protection value (sum of FPV of all blocks), whereas the smallest 20th percentile of the proposed harvest blocks (the 1st quintile) contained less than 12% of those values (Table 1).

In order to gain insight into how other factors might influence the FPV, we computed the FPV per unit area (FPV/block size) for each harvest block (Fig. 4*b*). We found the blocks with

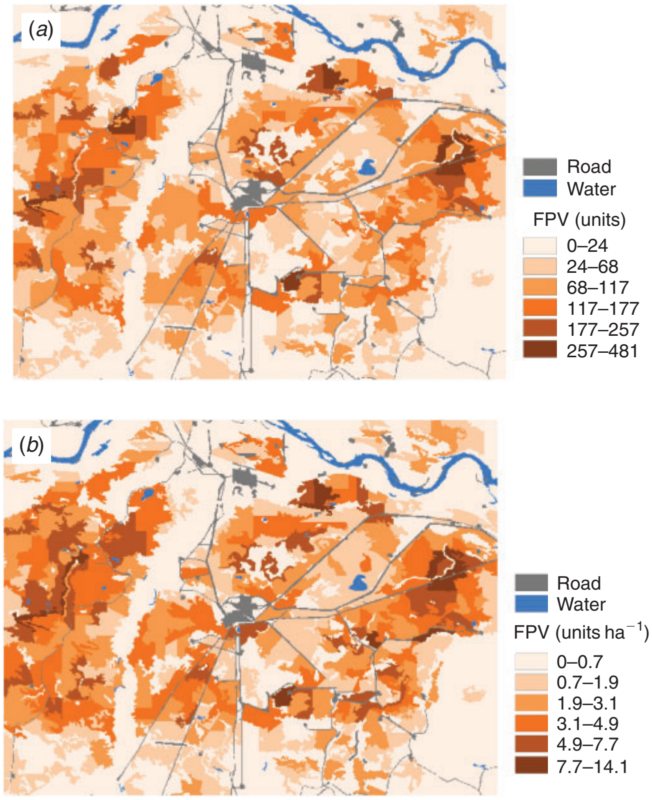


**Fig. 4.** Fire protection values by block; (*a*) total units, and (*b*) units per hectare.


**Fig. 5.** Location of blocks with extreme fire protection values. The blocks with highest fire protection values were located close to high timber volume areas, and blocks with lowest fire protection values close to low volume areas.

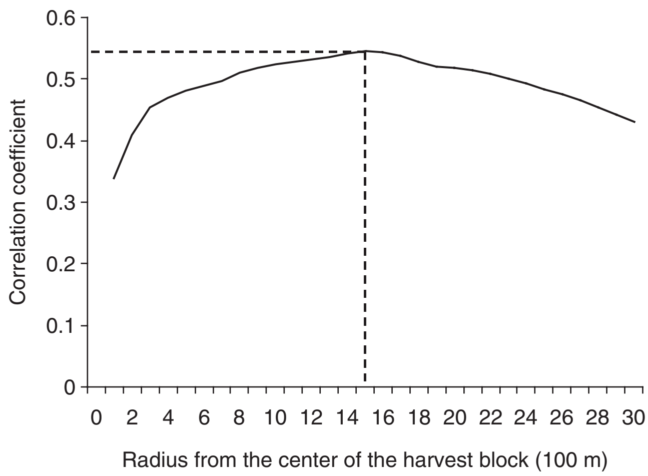


**Fig. 6.** Correlation between fire protection value and timber volume in the area surrounding the harvest block. The maximum correlation was found for a 700-ha neighbourhood, represented by a 1500-m radius.

**Table 1. Impact of harvest block size on fire protection values**
The largest 20% of the blocks (5th quintile) contained close to 31% of the total fire protection value

| | Total area | | Fire protection value | |
|---|---|---|---|---|
| | (ha) | (%) | (units) | (%) |
| Quintile 1 | 1570 | 12.1 | 4108 | 11.4 |
| Quintile 2 | 2121 | 16.4 | 5673 | 15.7 |
| Quintile 3 | 2511 | 19.4 | 6751 | 18.6 |
| Quintile 4 | 3066 | 23.7 | 8493 | 23.5 |
| Quintile 5 | 3697 | 28.5 | 11 182 | 30.9 |

the highest FPVs were located close to areas that had relatively high concentrations of stands with high merchantable timber volumes. Blocks with lowest FPVs were close to low-volume forest stands or close to natural fire spread barriers such as rivers or roads (Fig. 5). In Fig. 5, we highlighted the 3% of the harvest blocks (14 blocks) that had highest and lowest FPVs. The 3% of the blocks with highest values contained 9.7% of the total FPV of the forest, whereas the 3% with lowest FPVs contained less than 0.20% of this value.

We also carried out a neighbourhood analysis to investigate the relationship between the FPV of a harvest block and the timber volume in the surrounding blocks. For each block, we calculated the timber volume in the surrounding area within different radii from the centre of the block, and analysed the correlation between its FPV and this volume (Fig. 6). The harvest blocks averaged 27.9 ha in size and ranged from 13.4 to 46.4 ha, so if we enclose a block in a circle with a radius less than 300–400 m, most of the volume within that circle will be the block's volume. With larger-radii containing volumes of the neighbouring blocks, the correlation coefficient increased and attained its maximum value (0.55) for a 1.5-km radius, which represents a 700-ha neighbourhood. Beyond this distance, the correlation started to decrease again because the probability that a fire will travel that far from the central block decreases, and that volume will have a lower impact on a block's FPV. We therefore used a 1.5-km radius, grouped the harvest blocks by timber volume in their vicinity, and averaged their FPVs. We found that the larger the volume in the neighbourhood of a harvest block, the higher the FPV in the harvest block (Table 2).

Fuel type or forest cover type was another important factor that helped explain why fire protection values varied from block to block. The average FPV for the study area was 2.79 units $ha^{-1}$, but we found important differences among species as illustrated

**Table 2. Impact of the presence of merchantable timber within 1.5 km on the fire protection value of a harvest block**

| Volume ($10^3$ $m^3$) | Protection value (units $ha^{-1}$) |
|---|---|
| 0–10 | 0.54 |
| 10–20 | 0.61 |
| 20–30 | 1.27 |
| 30–40 | 2.28 |
| 40–50 | 2.84 |
| 50–60 | 3.37 |
| 60–70 | 4.44 |
| 70–80 | 5.61 |

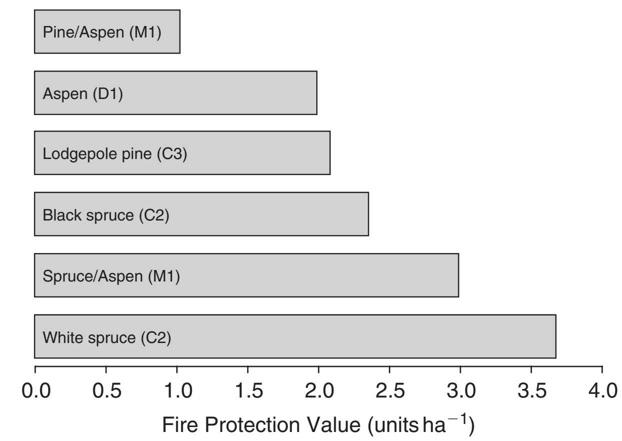


**Fig. 7.** Differences in fire protection values by forest cover type (Canadian Forest Fire Behaviour Prediction fuel type in parentheses).

in Fig. 7. Spruce (primarily white spruce or what forest fire behaviour specialists refer to as the C-2 fuel type) was more prone to support fire spread than other fuel types (e.g. aspen).

Fire ignition probabilities tended not to vary significantly from cell to cell, so it was difficult to visually identify their influence on FPVs. However, an analysis like the one made for the area (Table 1) showed similar results for ignition probabilities. Blocks with high FPVs were generally located in areas with high ignition probabilities. Harvesting such blocks would reduce the overall likelihood of fires starting in those blocks and subsequently spreading high value stands.

## Discussion

Our methodology produced quantitative assessments of the effect of harvesting specific blocks on fire damage in terms of the expected reduction in fire loss across the landscape. We used timber volume as our value at risk but our methodology could be used to assess the impact of such activities on any measurable values at risk. Our methodology identified crucial blocks that are located on fire paths that lead to high value areas as being crucial for reducing fire losses. Harvesting those blocks would therefore interrupt critical fire paths and force fires to travel through areas with lower spread rates, increasing the chance of suppression and reducing potential losses. The identification of areas with high FPVs could also be used to prioritise areas for fuel treatment (Stephens 1998).

Some studies (Cumming 2001; Nunes *et al*. 2005) have shown that the fuel in the vicinity of a fire explained much of the variation in the area burned. Our results showed that the characteristics of a harvest block's neighbourhood, specifically the stock of valuable timber in its vicinity, were an important factor in estimating the FPV of a block. Cutting blocks inside large continuous areas of valuable timber, which usually had the highest FPVs, might fragment the landscape and reduce fire losses. However, blocks with lowest FPVs were located in areas with sparse forest, close to natural fire spread barriers such as rivers or roads or in the borders of the study area. The edge effect results from the fact that there is no incentive to protect high-value harvest blocks outside the borders. This anomaly could be addressed by including all values within some distance of the border in the analysis. If that were done, the FPV of the blocks close to the border would reflect the effect of interrupting fire spread to high value border cells.

We also simplified the impact of fire suppression on burned area. We modelled the ignition of all fires and assumed they would spread under extreme fire weather conditions that would typically be associated with escaped fires. As only a small proportion of fires actually escape initial attack and spread over large areas (typically of the order of 5%), our FPV values were overestimates of the true economic impact of harvesting on reducing fire loss. However, because we needed only rank cells with respect to their impact on landscape level fire loss, this was not a serious problem. In the future, we hope to refine our model by developing an escaped fire probability model that relates the probability that a fire escapes initial attack to fuel, weather and level of protection measures. Further in that vein, our model could be enhanced by modelling the impact of the establishment of fuel breaks that could serve as anchor points for large fire suppression operations, but that is beyond the scope of our analysis.

Other factors such as block size, forest cover type and ignition probability also influenced the FPV of a block. As expected, the size of the harvest blocks had an important effect on the fire spread reduction. The larger the block harvested, the greater its FPV, in other words, the greater the effect on reducing the potential fire losses. This makes sense, as when a larger area of timber (which serves as fuel) is removed, the timber in that block is protected from fire, no ignitions will occur in the harvested area and more fires will be forced to use longer paths to spread between ignition cells and cells that contain values at risk. In addition, the forest cover type was another factor defining the FPV because blocks with more flammable vegetation (coniferous) tended to have higher FPVs. The relation between FPV and cover type we obtained should be seen only as a general indication about how our methodology works, and not as evidence of fuel type flammability, as other relevant factors (e.g. topography and age) were not considered in the present analysis. Finally, the probability of ignition played an important role in the FPV estimations because blocks with high FPVs were generally located in areas with high ignition probabilities. This happened because removing these blocks reduced fire occurrence and fire spread.

We made several simplifying assumptions in the development of our methodology. We assumed fire cannot spread through a harvested block; this could easily be generalised to support slower spread rates through treated blocks, allowing the evaluation of fuel management measures. We also ignored fire intensity as we were concerned with only escaped fires that burn under severe conditions, during which it is reasonable to assume all the merchantable timber volume in a burned cell is lost. If that is not the case, partial timber losses would probably be affected in a similar way and would not produce significant differences in the relative FPVs. And finally, we assumed fires cannot burn through (or more precisely, spot across) roads and other non-flammable barriers and that assumption might have produced underestimates of the FPV of blocks that would support spotting crown fires and were located close to or adjacent to such barriers. However, the FPV model could be modified by incorporating probabilistic spotting processes once fire spotting is better understood.

Our FPV evaluation methodology was based on the assumption that if you cut a harvest block you force a fire to travel from cell *i* to cell *j* over the second fastest path. Suppose there are two second-fastest paths. This is not a problem because it does not matter which of the two second-fastest paths are used. However, suppose we have two fastest paths. Then cutting one of them will accomplish nothing as the remaining path will carry the fire at the same speed. When you evaluate the second path, you will encounter the same problem. We refer to this as the 'levee problem'. If you build a long levee to prevent flooding, you waste your money if you leave one small gap in the levee. The solution, of course, would be to build all of the levee to the same height.

The analogy for our problem is as follows. Suppose we have two best paths from cell *i* to cell *j*. If you consider the first of these two best paths and you want to determine the value of cutting it, you have to consider cutting it and all the other best paths that have the same travel time from cell *i* to cell *j*. In order to do so, we would have to construct a virtual compound best path from cell *i* to cell *j* by aggregating all the fastest paths from cell *i* to cell *j* into one compound virtual path. Those fastest paths may have some cells in common and we would have to fracture the entire compound virtual path. In order to do that, we would need to find the minimum number of cells to cut from the set of cells forming the best compound virtual path, so there would be no good paths left in the compound virtual path. The formulation and solution of a network 'breaking' model that could be used to partition cells *i* and *j* into two separate subtrees, what graph theorists would refer to as a network bisection problem, is beyond the scope of this paper and a subject for further research.

Finally, recall that our methodology is designed to assess the forest-level impact of harvesting each block in isolation from all the other blocks on the landscape. As we noted in the description of our methods, the net effect of harvesting two blocks k and k′ would be therefore not be the sum of FPV(k) and FPV(k′). Our approach is designed to identify crucial blocks that have a significant impact on the fire spread to valuable areas in the landscape. Once those crucial blocks have been identified, one must develop and evaluate alternative strategies composed of sets of blocks that can be harvested together. Suppose for example that $\{k_1, k_2, \ldots, k_n\}$ denotes a set of blocks (or a virtual superblock) that can be harvested simultaneously. One could use our methodology to evaluate the effect of harvesting that set of blocks together. Evaluating all feasible virtual superblock alternatives would no doubt be computationally intensive, but one could incorporate our block-specific FPV in a hierarchical heuristic procedure to identify good sets of blocks to harvest.

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## References

Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**, 83–96. doi:10.1016/J.FORECO.2005.01.034

Ahuja RK, Magnanti T, Orlin YJ (1993) 'Network Flows: Theory, Algorithms, and Applications.' (Prentice Hall: Englewood Cliffs, NJ)

Bevers M, Omi PN, Hof J (2004) Random location of fuel treatments in wildland community interfaces: a percolation approach. *Canadian Journal of Forest Research* **34**, 164–173. doi:10.1139/X03-204

Cumming SG (2001) Forest type and wildfire in the Alberta boreal mixedwood: what do fires burn? *Ecological Applications* **11**, 97–110. doi:10.1890/1051-0761(2001)011[0097:FTAWIT]2.0.CO;2

Cunningham AA, Martell DL (1973) A stochastic model for the occurrence of man-caused forest fires. *Canadian Journal of Forest Research* **3**, 282–287. doi:10.1139/X73-038

Finney MA (2001) Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *Forest Science* **47**, 219–228.

Finney MA (2002) Fire growth using minimum travel time methods. *Canadian Journal of Forest Research* **32**, 1420–1424. doi:10.1139/X02-068

Finney MA (2005) The challenge of quantitative risk analysis for wildland fire. *Forest Ecology and Management* **211**, 97–108. doi:10.1016/J.FORECO.2005.02.010

Finney MA, Seli RC, McHugh CW, Ager AA, Bahro B, Agee JK, (2006) Simulation of long-term landscape-level fuel treatment effects on large wildfires. In 'Fuels Management – How to Measure Success: Conference Proceedings'. 28–30 March 2006, Portland, OR. (Eds PL Andrews, BW Butler) pp. 125–147. (USDA Forest Service, Rocky Mountain Research Station: Fort Collins, CO) Available at http://www.fs.fed.us/rm/pubs/rmrs_p041/rmrs_p041_125_147.pdf [Verified 16 October 2007]

Forestry Canada Fire Danger Group (1992) Development and structure of the Canadian Forest Fire Behavior Prediction System. Information report ST-X-3. (Ottawa, ON)

Gonzalez JR, Palahi M, Pukkala T (2005) Integrating fire risk considerations in forest management planning in Spain – a landscape-level perspective. *Landscape Ecology* **20**, 957–970. doi:10.1007/S10980-005-5388-8

Graham RT, Harvey AE, Jain TB, Tonn JR (1999) The effects of thinning and similar stand treatments on fire behavior in western forests. USDA Forest Research Service, Pacific Northwest Research Station General Technical Report PNW-GTR-463. (Portland, OR)

Gustafson EJ, Zollner PA, Sturtevant BR, He HS, Mladenoff DJ (2004) Influence of forest management alternatives and land type on susceptibility to fire in northern Wisconsin, USA. *Landscape Ecology* **19**, 327–341. doi:10.1023/B:LAND.0000030431.12912.7F

Hirsch K, Kafka V, Tymstra C, McAlpine R, Hawkes B, Stegehuis H, Quintilio S, Gauthier S, Peck K (2001) Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. *Forestry Chronicle* **77**, 357–363.

Johnson KN, Sessions JF, Gabriel J (1998) Integrating wildfire into strategic planning for Sierra Nevada forests. *Journal of Forestry* **96**, 42–49.

Kourtz PH, Nozaki S, O'Regan W (1977) Forest fires in the computer – a model to predict the perimeter location of a forest fire. Fisheries and Environment Canada Information Report FF-X-65. (Ottawa, ON)

Loehle C (2004) Applying landscape principles to fire hazard reduction. *Forest Ecology and Management* **198**, 261–267. doi:10.1016/J.FORECO.2004.04.010

Martell DL (1994) The impact of the fire on timber supply in Ontario. *Forestry Chronicle* **70**, 164–173.

Natural Regions Committee (2006) Natural regions and subregions of Alberta. (Eds DJ Downing, WW Pettapiece) Government of Alberta. Publication Number T/852. (Edmonton, AB)

Nunes MCS, Vasconcellos MJ, Pereira JMC, Dasgupta N, Alldredge RJ, Rego FC (2005) Land cover type and fire in Portugal: do fires burn land cover selectively? *Landscape Ecology* **20**, 661–673. doi:10.1007/S10980-005-0070-8

Parisien MA, Junor DR, Kafka VG (2006) Using landscape-based decision rules to prioritize locations of fuels treatments in the boreal mixedwood of western Canada. In 'Fuels Management – How to Measure Success: Conference Proceedings'. 28–30 March 2006, Portland, OR. (Eds PL Andrews, BW Butler) pp. 221–236. (USDA Forest Service, Rocky Mountain Research Station: Fort Collins, CO) Available at http://www.fs.fed.us/rm/pubs/rmrs_p041/rmrs_p041_221_236.pdf [Verified 16 October 2007]

Pollet J, Omi PN (2002) Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* **11**, 1–10. doi:10.1071/WF01045

Roloff GJ, Mealey SP, Clay C, Barry J, Yanish C, Neuenschwander L (2005) A process for modeling short- and long-term risk in the southern Oregon Cascades. *Forest Ecology and Management* **211**, 166–190. doi:10.1016/J.FORECO.2005.02.006

Sampson RN, Sampson RW (2005) Application of hazard and risk analysis at the project level to assess ecologic impact. *Forest Ecology and Management* **211**, 109–116. doi:10.1016/J.FORECO.2005.02.004

Stephens SL (1998) Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests. *Forest Ecology and Management* **105**, 21–35. doi:10.1016/S0378-1127(97)00293-4

Thompson D (Ed.) (1998) 'Oxford Dictionary of Current English: New Revised Edn.' pp. 661–673. (Oxford University Press: Oxford)

van Wagtendonk JW (1996) Use of a deterministic fire growth model to test fuel treatments. In 'Sierra Nevada Ecosystem Project: Final Report to Congress, Vol. II. Assessments and Scientific Basis for Management Options'. University of California, Davis, Centers for Water and Wildland Resources. pp. 1155–1165. (Davis, CA) Available at http://www.farsite.org/downloads/farsite/publications/vii_c43.pdf [Verified 16 October 2007]

Van Wagner CE, Pickett TL (1987) Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, Forestry Technical Report 35. (Ottawa, ON)

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