Estimating harvest schedules and profitability under the risk of fire disturbance

Brian Peter and John Nelson

Abstract: Incorporating fire disturbance into sustainable forest management plans is necessary to provide estimates of variation around indicators for harvest levels, growing stock, profitability, and landscape structure. A fire disturbance model linked to a harvest simulator was used to estimate the probability of harvest shortages under a range of harvest levels and fire suppression scenarios. Results were then used to estimate "sustainable" harvest levels based on a risk tolerance to harvest shortages and the effects of fire suppression. On a 288 000 ha forest in northeastern British Columbia, the cost of historical fire disturbance was estimated at $4 million per year in terms of foregone harvest profits. Suppressing 98.3% of disturbance events to 30% of their historical size had a value of $1.8 million per year. Higher levels of risk tolerance were associated with increased harvest levels and short-term profits, but as timber inventories were drawn down, average long-term profits became volatile. The modelling framework developed here can help to determine resilient forest management strategies and estimate the future flow and variability of harvest volumes, profits, and landscape conditions.

Résumé : Il est nécessaire d'incorporer les perturbations causées par le feu dans les plans d'aménagement forestier durable pour obtenir des estimations de la variation dans les indicateurs de niveau de récolte, de volume sur pied, de rentabilité et de structure du paysage. Un modèle de perturbation due au feu relié à un simulateur de récolte a été utilisé pour estimer la probabilité de rupture de stock compte tenu d'une gamme de niveaux de récolte et de scénarios de suppression des feux. Les résultats ont ensuite été utilisés pour estimer les niveaux de récolte soutenue sur la base d'une tolérance aux risques de rupture de stock et aux effets de la suppression des feux. Le coût des perturbations passées dues au feu a été estimé à 4 $ millions par année en termes de profits qu'aurait pu rapporter la récolte dans une forêt de 288 000 ha située dans le nord-est de la Colombie-Britannique. La suppression de 98,3 % des perturbations dans le but d'en limiter les effets à 30 % de la superficie qu'elles ont réellement affectée a été évaluée à 1,8 $ millions par année. Les niveaux plus élevés de tolérance au risque étaient associés à des niveaux de récolte et des profits à court terme plus élevés, mais les profits moyens à long terme devenaient volatiles à mesure qu'on réduisait les volumes de bois sur pied. La structure du modèle développé dans cette étude pourrait aider à définir des stratégies d'aménagement forestier résilientes et à estimer l'évolution future et la variabilité des volumes de récolte, des profits et de l'état du paysage.

[Traduit par la Rédaction]

Introduction

Fire is the dominant natural disturbance agent in Canada's boreal forests, and it plays an important role in ecosystem structure and function. These forests are also an important source of fibre, and the economic cost of fire in these forests is significant. For example, in British Columbia forest fires burn an average of 25 000 ha/year and annual fire suppression expenditures average CAN$56 million (British Columbia Ministry of Forests 2003). Fire-dominated forests present challenges for forest managers that need to set sustainable harvest levels, develop fire suppression programs, advise investors of risks to timber supply, and make informed predictions of how harvesting and natural disturbances influence landscape structure. Forecasts of harvest levels and future forest conditions that incorporate fire disturbance are especially important in the context of sustainable forest management plans, where indicators and targets need to be set for economic, ecological, and social criteria.

Incorporating fire disturbance into forest management planning presents challenges because of the wide variation in the frequency and severity of events and the uncertainty of where and when these events will occur. In this paper we use a risk-tolerance approach to estimate sustainable harvest levels and include the corresponding projections of timber inventories, profitability, and the abundance of old seral forests in the presence of fire. The fundamental concept is that "sustainable forest management" is relative. Managers, in-

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vestors, and other stakeholders have individual tolerances to losses incurred by fire, and a risk assessment of these losses can help them set sustainable harvest rates that reflect these tolerances. Our risk assessment is based on estimating harvest shortages that are expected to occur under a range of harvest levels and fire suppression scenarios. We develop a modelling framework that includes fire disturbance linked to a harvest simulator and apply it to a forest in northeastern British Columbia.

The objectives of this paper are to (1) estimate sustainable harvest rates based on the risk associated with fire disturbance, (2) determine timber inventories and old-seral forest that result from these harvest rates, and (3) determine profit patterns under different harvesting strategies and fire occurrence assumptions. We first provide a literature review of work that integrates fire disturbance into harvest scheduling models and various approaches used to incorporate the risk of fire in planning. In the methods section, we describe the forest used in the case study, and introduce a fire disturbance model and describe how it is linked to a harvest simulator. We then define indicator variables that are used to track key outputs. Results are then presented and discussed for the indicator variables under each harvest–disturbance scenario, including both cumulative effects and temporal trends over the simulations.

Literature review

Uncertainty is a pervasive factor in forest management. Courtney et al. (1997) divided uncertainty into four categories: (1) a single outcome that can be forecast with a level of precision; (2) several discrete outcomes with probabilities that may be estimated; (3) a continuum of possible outcomes that fall within a defined range; and (4) true ambiguity, where there is no basis to forecast the future. There are many sources of uncertainty in forest management, each of which can contain one or more of the aforementioned categories. For example, yield from individual stands can be different than predicted because of changing soil or climate conditions, fire, disease, or other biological factors (Kimmins 1990). In addition, data on which predictions are made can be subject to sampling or measurement errors (Weintraub and Abramovich 1995). At a landscape level, all of these factors, along with social, economic, and policy changes, create uncertainty in our forest management predictions (Kimmins and Sollins 1989). Hof et al. (1995, 1996) emphasized the importance of presenting model results that acknowledge the uncertainty of inputs and suggested methods for incorporating uncertainty in optimization models. Gadow (2000) showed ways in which risk analysis can be applied to forest management problems and noted that applications of risk analysis in forest planning are rare.

Integrating the uncertainty of fire (or other natural disturbances) into forest models is relatively recent. van Wagner (1983) provided one of the first examples of explicit disturbance simulation in a nonspatial timber supply model. The resulting losses to timber supply were demonstrated to be greater than the actual volume burned. This is because fire activity does not simply mimic harvesting. It affects stands of various ages, extending the average amount of time required to produce a merchantable stand, leading to a harvest

consisting of younger, lower volume stands than would occur in the absence of fire. Even fires that occur in young stands with little or no merchantable volume still impact long-term harvest rates. van Wagner (1983) further demonstrated that when harvest rates are sufficiently reduced, the harvest becomes relatively insensitive to the amount of fire. Reed and Errico (1986) reached a similar conclusion when approximating optimum harvest schedules in the presence of stochastic fire disturbance. Martell (1994) used a modified version of the Reed and Errico (1986) model to show that fire suppression in Ontario has economic benefits. Keeping a buffer stock of timber for natural disturbance risks can produce stable and in some cases higher long-term harvest rates when harvest ages are pushed beyond the economic rotation age (Boychuck and Martell 1996).

Examples of spatially explicit forest models that incorporate natural disturbance also exist. Boychuck and Perera (1997) used FLAP-X to simulate simple stochastic models of natural disturbance, to determine long-term frequency distributions of old-growth and recently disturbed area. LANDIS (Gustafson et al. 2000) simulates ecological dynamics, including various forms of disturbance. Kurz et al. (2000) developed the simulation tool TELSA, and Klenner et al. (2000) used TELSA to illustrate that fire disturbance can increase reserve requirements for vulnerable habitat types. SELES (Fall and Fall 2001) can simulate stochastic events across a landscape and has been used to estimate landscape patterns resulting from forest growth, disturbance, and harvesting (Fall 1999). Armstrong (2004) assessed timber supply sustainability alongside stochastic fire disturbance, using multiple runs with a nonspatial model. Following harvest and disturbance in each period, the long-term harvest was recalculated. He found that reducing the harvest below the calculated long-term harvest increased the probability of a sustainable harvest and that this can be used to choose harvest rates that reflect a tolerance for risk.

Although the risk associated with harvest rates has been demonstrated by Armstrong (2004), different approaches to this problem still exist. The idea of buffering against the effects of natural disturbance on timber supply has been put forward by others (Boychuck and Martell 1996; Nelson 2003a), though ways of quantifying this buffer and the dynamics of buffer stocks through time have not. The impact of disturbance on the profits from harvesting is also an important factor and can provide a measure of the value of suppression as well as the cost of disturbance itself. We are also interested in how the resulting forest structure, particularly old forests, are affected by fire disturbance.

Materials and methods

Study area description

Block 4 of Tree Farm License (TFL) 48 is located in northeastern British Columbia, near the community of Chetwynd (Fig. 1), and contains tree species that include lodgepole pine (*Pinus contorta* Dougl. ex Loud.), trembling aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* (Moench) Voss), hybrid spruce (*Picea engelmannii* Perry ex Engelm. × *Picea glauca*), and black spruce (*Picea mariana*). Engelmann spruce (*Picea engelmannii*) and subal-

Fig. 1. Study area location and natural disturbance regimes.
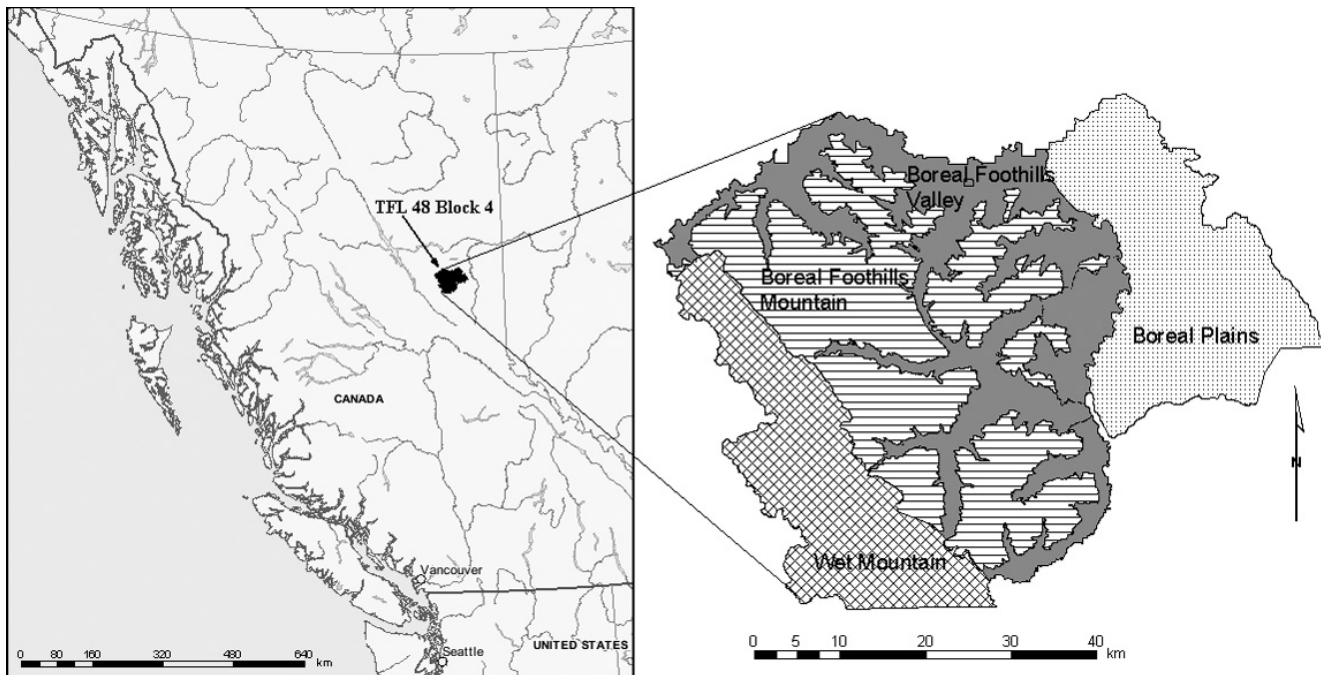
pine fir (*Abies lasiocarpa* (Hook.) Nutt.) also occur at higher elevations.

Fire is the most significant natural disturbance in the study area and accounts for the majority of nonrecoverable losses. Four Natural Disturbance Units (NDUs) occur in the study area, which are characterized in terms of disturbance rates and patch size distributions (DeLong 1998), and these are summarized in Table 1. Fire is the predominant disturbance agent in all of the NDUs, with the exception of the wet mountian NDU, where stands are typically subject to endemic levels of various insects and diseases. The Boreal Foothills NDU (Mountain and Valley) is dominated by wildfires, resulting in a mosaic of even-aged forest stands in patches of less than 10 000 ha. The Boreal Plains NDU is also dominated by fire, although fires are more frequent and larger, creating patches of up to 40 000 ha. While other studies have found much larger disturbance sizes in northern forests (e.g., Payette et al. 1989; Cumming 2001), DeLong (1998) suggests that mountainous topography and a forest mosaic that includes wetter, cooler stands limits the size of fires in this area. All fires in the study area are subject to suppression. In the last 15 years it is estimated that approximately 15 000 m^3 of timber have been lost to fires.

Harvest scheduling model

For harvest scheduling, we use the FPS-ATLAS model (Nelson 2003*b*). FPS-ATLAS is a polygon-based harvest-scheduling simulator that allows for modelling with spatial constraints including adjacency, seral stage levels, and spatially located reserves. Polygons represent forest stands and are assigned to vegetation types (referred to as stand groups), which relate the age of the polygon to attributes such as harvest volume and specify the age at which harvesting or other treatments can be applied.

Block 4 of TFL 48 covers an area of approximately 288 000 ha and includes 70 777 polygons, which are classi-

Table 1. Disturbance parameters of Natural Disturbance Units (NDU) within Tree Farm License 48 block 4.

NDU	Area (ha)	Disturbance cycle (years)	Avg. disturbance size (ha)
Boreal plains (upland)	64 530	100	200
Boreal foothills			
Valley	75 683	120	90
Mountain	94 880	150	80
Wet mountain	53 493	900	62
Total	288 586		

fied into 141 stand groups. Yield curves for each stand group were derived from the FORECAST Ecosystem Simulation Program (Kimmins et al. 1999). The model was then set up to harvest polygons in clusters, or "super-blocks", to better represent operational harvest block configurations. A set of approximately 6000 superblocks (60-ha target size) was used. All polygons are assigned to one of the NDU regimes.

Minimum harvest ages for all stand groups were set to the age where mean annual increment is maximized. Stands were prioritized for harvesting using a modified oldest-first rule, where the number of years beyond the minimum harvest age is used to assign priority. This harvest priority selects stands that have current ages well beyond the minimum harvest age (e.g., far beyond the maximum mean annual increment) and tends to convert them to regenerated stands more quickly than the oldest-first rule, which simply targets the oldest stands, regardless of their growth rate (which may be low, but still close to the maximum mean annual increment).

Twenty-year adjacency rules were applied to harvesting; however, this constraint was relaxed for blocks smaller than 10 ha and for the first decade of harvesting, where a large number of polygons were constrained by this requirement.

Forest policy over the past decade allowed only small harvest openings, and the change to 60-ha openings requires a transition period where some adjacency rules are relaxed. Simulations were conducted in 10-year time-steps, with all activity scheduled at the midpoint of the decade. A simulation length of 300 years was used, which covers approximately three rotations.

Disturbance model

Fire events were simulated using an option in FPS-ATLAS that pauses the simulation at each period and then calls an external disturbance program. An overview of disturbance and harvesting within FPS-ATLAS is shown in Fig. 2. Stands are disturbed and made available for harvest at their current age, but in a different stand group that yields a reduced volume (70%), to account for fire damage. If salvaged, the stands are converted to a managed stand group. If not salvaged, the next execution of the disturbance model resets the stand to an unmanaged stand group. Salvageable stands received top priority for harvesting, ahead of the undisturbed stands in the harvest queue. We assume that stands are only available for salvage for one period following the disturbance, and if not salvaged become nonrecoverable losses.

All disturbance in our model is assumed to consist of stand-replacing fires, and fire occurrence is assumed to be independent of stand age. This is a common assumption for natural disturbance simulations in northern forests (Armstrong 2004; Boychuck and Perera 1997; Martell 1994; van Wagner 1983). Because of the age-independent assumption, reburning of polygons in the same simulation period can occur. Fires do not generally consume all large fuels, and sufficient fine fuels to support fire may reestablish quickly (Frelich 2002; Johnson et al. 2001). While this may be a rare occurrence within the same year, it can occur within a 10-year period, which corresponds to the time step used by our simulation models. The reburn assumption becomes important when very high disturbance rates apply, but this is not the case in block 4 of TFL 48.

To model temporal variation in disturbance rates we employ two stochastic functions. First, to account for the variation in fire occurrence, we use an overdispersed Poisson distribution, based on work by Cumming (2000) and Cumming and Wong (2002). Second, an exponential distribution is used to model the variation in fire size. The Poisson distribution (eq. 1) is used, with a mean based on the expected numbers of events (estimated using eq. 2) and a multiplicative "overdispersion" factor that is gamma distributed (eq. 3), with a mean of 1. Poisson–gamma mixtures (which yield negative binomial distributions) are commonly used to describe count data that have a variance in excess of the mean (overdispersion) (Cameron and Trivedi 1998):

$$[1] \qquad f(y) = \frac{e^{-\lambda}\lambda^y}{y!}$$

where the expected value and the variance are equal to λ.

The expected number of events (E) is

$$[2] \qquad E = \frac{abc}{d}$$

where the average disturbance rate (decimal proportion of the landscape per year) is a, the area (hectares) is b, the period length (years) is c, and the average event size (hectares) is d.

$$[3] \qquad f(y) = \frac{\delta^\phi}{\Gamma(\delta)} y^{\delta-1} e^{-y\phi}$$

where δ and ϕ are shape and scale parameters, the average or expected value is δ/ϕ, the variance is δ/ϕ^2, and $\Gamma(\bullet)$ is the gamma function.

The expected number of events from eq. 2 is constant through all simulations and is estimated by taking the inverse of the disturbance cycle for each NDU, multiplied by both the area of the NDU and the period length, and then divided by the average event size. The actual number of events in each simulation period is then determined as follows: First, a gamma variate is drawn that multiplies the expected number of events in each regime, which either increases or decreases them. A common gamma variate is used across all regimes in each period, since we assume extra-Poisson variation is due to weather or other factors that affect all NDUs in a similar way. Poisson variates are then drawn from the adjusted expected number of events and are used to assign the final number of disturbance events for the period in each regime. For example, assume that two regimes have an expected number of disturbance events per period of 3 and 5, respectively ($\lambda_1 = 3.0$, $\lambda_2 = 5.0$). If the gamma draw is 1.2, the adjusted expected number of events in that particular period would be 3.6 and 6.0, respectively. Poisson draws to determine the actual number of events are then made based on $\lambda_1' = 3.6$ and $\lambda_2' = 6.0$.

To return an expected value of 1, eq. 3 is reduced to a single parameter distribution by setting $\delta = \phi$ (Cameron and Trivedi 1998). Higher values for this parameter create less variation in the number of events, and lower values create more variation. The gamma parameter was estimated from the literature (Cumming 2000; Cumming and Wong 2002) and was set to a comparatively conservative estimate of $\delta = \phi = 15$, to reflect the cooler, wetter conditions characteristic of our study area.

The size of disturbance events is controlled by stochastically generated patch size targets. Fire size distributions in northern forests have been characterized in a variety of ways, including discrete size classes (Payette et al. 1989), exponential and normal distributions (Stocks 1991), and exponential distributions of the logarithm of fire size (Cumming 2001). Patch size targets in this study are drawn from an exponential distribution (eq. 4). The distribution is parameterized based on the average disturbance size for each NDU:

$$[4] \qquad f(y) = \frac{1}{\mu} e^{-y/\mu}$$

where the average or expected value is μ and the variance is μ^2.

When a disturbance event is initiated, a random polygon is first chosen as a seed for the event, a patch size target is generated, and the event spreads to adjacent polygons until either the patch size target is reached or there are no more eligible adjacent polygons. As each polygon is disturbed, its

Fig. 2. Harvesting and disturbance routines repeated in each period during a simulation.
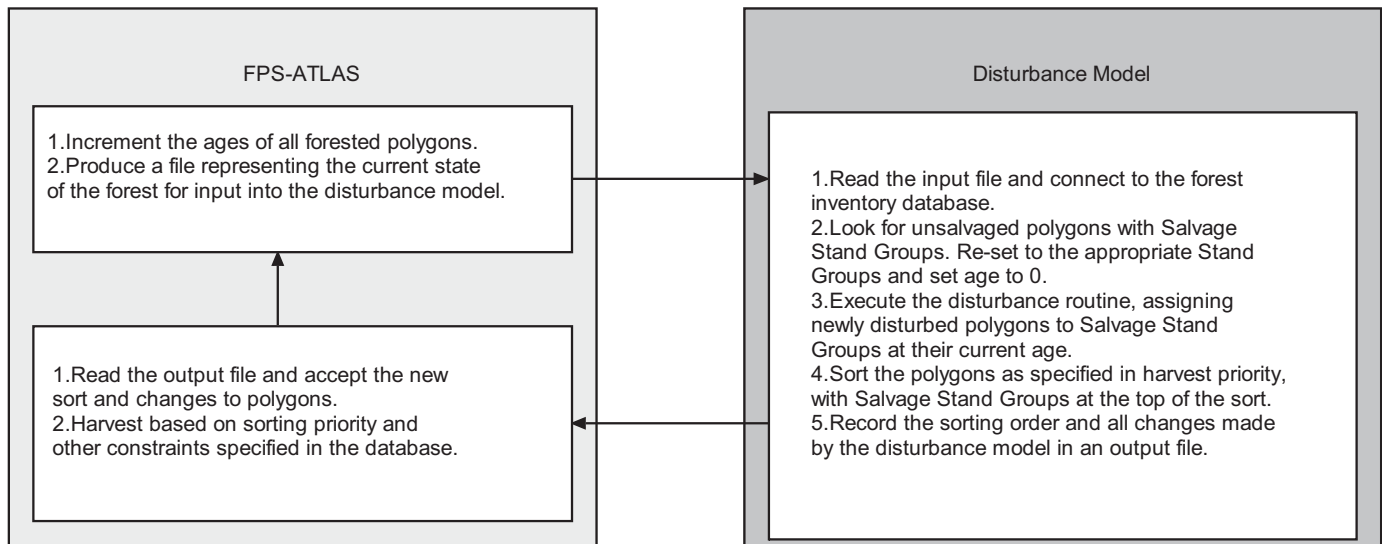
adjacent polygons are added to a queue and evaluated in sequence (the order in which they appear in the database) for their eligibility for disturbance. Eligible polygons are disturbed and made ineligible for being redisturbed until the current event is complete. Patches are allowed to spread in any direction, which in most cases allows them to achieve the target size. Spread direction was not included in the patch building process, as the model is simply trying to implement a patch on the landscape, rather than mimic a specific event. Shape characteristics such as area–perimeter ratio and orientation relative to slope, aspect, and wind direction were not included. Although patches will spread in a roughly circular fashion when all adjacent polygons are eligible, the exclusion of ineligible vegetation types such as swamps, rivers, and lakes effectively creates fire breaks on the landscape, leading to disturbance shapes that correspond to topographic features. Correlation between the number of events per unit time and the sizes of events was also not included. Incorporating this correlation could have effects that include peak fire years of greater magnitude, if large fires are more likely when fires are numerous. While this correlation could easily be incorporated into the current model (for example, by linking disturbance sizes to the gamma draw), this is beyond the scope of this paper.

Indicator variables

Four indicator variables were tracked in all scenarios: (1) sustainable harvest targets, (2) harvestable stock, (3) percentages of late-seral area, and (4) profit. Multiple runs were made to determine average values and the range for these indicator variables. Details of the indicator variables are described next.

Sustainable harvest target

To choose a "sustainable" harvest target, we estimate a relationship between harvest rates and the risk that those rates cannot be met in every time period. To determine this relationship, a series of harvesting scenarios are repeatedly simulated along with stochastic disturbance, and the proportion of simulations that fail to achieve the minimum acceptable

harvest volume are recorded. The minimum acceptable volume is defined as the harvest target minus a 10% tolerance. A logistic regression line is estimated from the resulting failure pattern with maximum likelihood estimation, using Stata® 7.0 software (StataCorp. 2001). Sustainable harvest targets are chosen using a risk tolerance of 10% (i.e., the minimum acceptable volume can be achieved in 9 of 10 simulations).

Harvestable stock and late-seral area

We define harvestable stock as the quantity of timber that is available for harvest in a period, when all constraints are considered. Harvests are constrained by periods when the harvestable stock and the harvest are equal and indicate the absence of slack or buffers in the system during these periods. Multiple disturbance simulations were conducted to determine the average and range of variation in harvestable stock. We also track the percentage of late-seral area, which we define as stands older than 140 years.

Profit

Delivered wood costs were used to determine profit for each period of the harvest schedule. Log-grade distributions were generated from the FORECAST model for each species within each stand group, and prices for log grades were assumed to be $35/m^3 for pulp, $65/m^3 for small sawlogs, $85/m^3 for large sawlogs, and $100/m^3 for peelers. Harvest costs were assumed to be $35/m^3 for ground-based systems, $85/m^3 for cable systems, and $65/m^3 for mixed cable and ground-based systems. An additional $3/m^3 was added to account for administration and planning expenses. A cost of $2000/ha was included to cover regeneration costs. All costs are assumed to be independent of the product mix, and the management of stands of the same type (stand group) is assumed to be consistent across the study area. To estimate transportation costs, a computer-generated road network was developed for the entire landscape that consisted of approximately 7000 km of road (Anderson and Nelson 2004; Seely et al. 2004). Road construction, deactivation, and reactivation costs were determined for each harvest schedule based on the timing of harvests and the class of roads projected.

Fig. 3. Estimated risk for harvest targets for each scenario: (*a*) historical disturbance and (*b*) suppression.
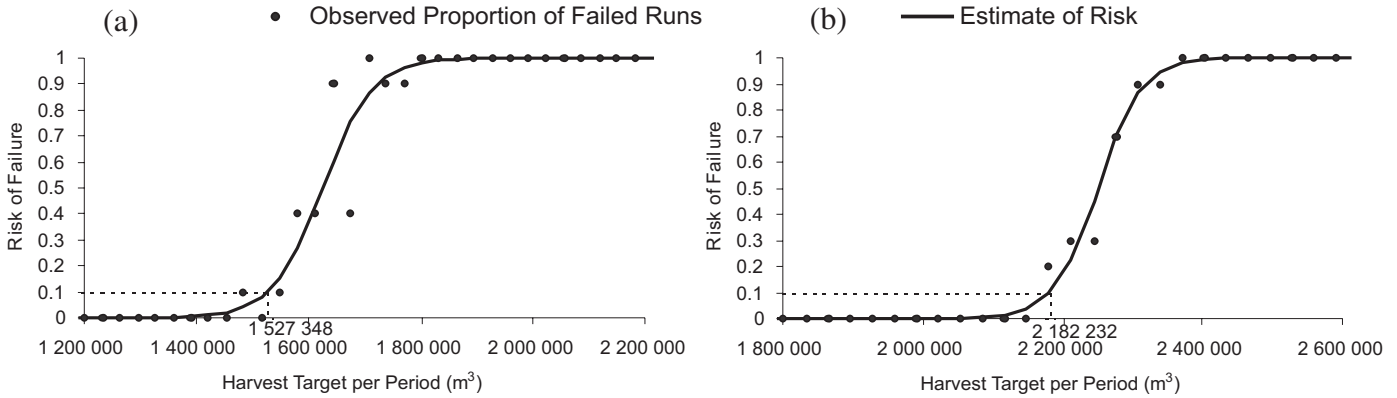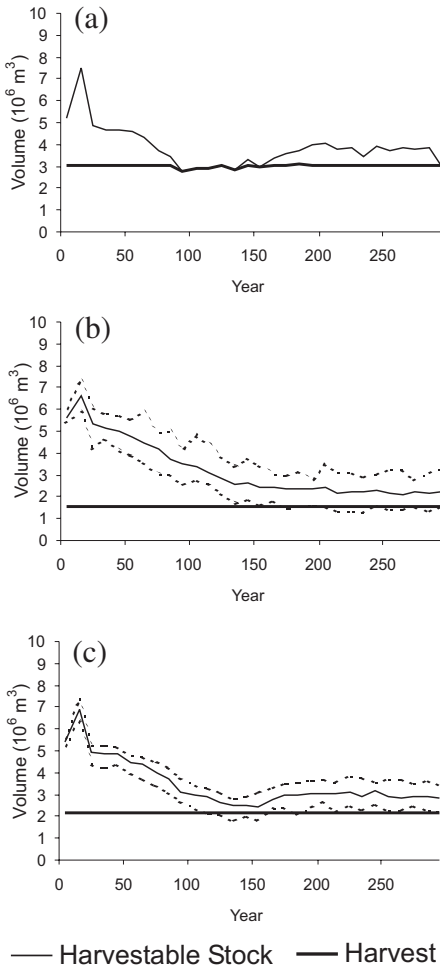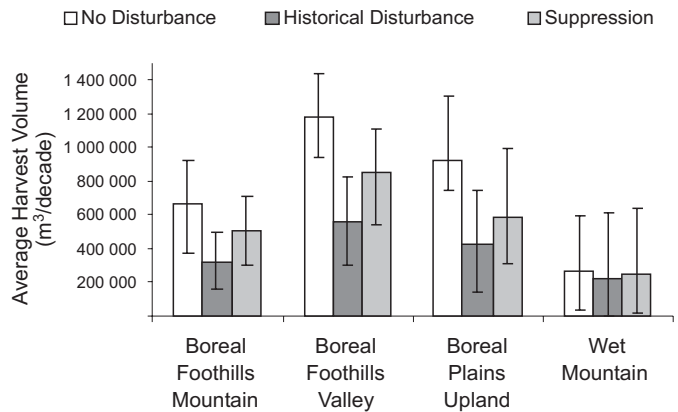

Fig. 4. Sustainable even-flow harvest target and harvestable stock: (*a*) no disturbance, (*b*) historical disturbance, and (*c*) suppression.

Fig. 5. Harvest flows by Natural Disturbance Unit.

class 3 roads, and $25 000 for class 4 roads. Hauling costs were estimated to be $0.10·m^{-3}·km^{-1}.

Once the revenue and cost data were generated, the profit was calculated for each period. The profit calculation represents the total conversion return, which would typically be distributed as stumpage payments to a forest owner, profits to forest companies, and taxes to government. Profits were discounted using a 4% discount rate to obtain net present values.

Disturbance and harvest scenarios

We formulated three scenarios to examine how fire disturbance influences the harvest schedule and forest structure. First, the base case scenario assumes no disturbance aside from harvesting and represents the most optimistic estimate of harvest rates against which the other scenarios can be compared. Second, historical rates of disturbance were simulated along with harvesting, and the reduction in harvest required for sustainability was determined. Finally, harvesting was simulated with historical fire disturbance; however, fire suppression was included. In this scenario, we assume most events are suppressed to 30% their size, but some of the largest events are beyond control. It is estimated that approximately 97% of the fires in Canada are contained through fire suppression, although a small percentage escape and be-

Deactivation (occurs when the road will be inactive for at least 20 years) was assumed to cost $2000/km and reactivation $8000/km. Road construction costs used were $40 000 for class 1 roads, $35 000 for class 2 roads, $30 000 for

come very difficult to control (Hirsch 2003). Events that had an initial size target of 500 ha or greater were chosen to represent events that are beyond control, which resulted in approximately 1.7% of disturbance events escaping. Suppression priorities were assumed to be consistent across the study area. Additional simulations using the suppression scenario were conducted to explore different levels of risk tolerance. Harvest targets were set to reflect higher levels of risk tolerance (0.5 and 0.9).

In each scenario, the risk associated with a range of harvest targets was first identified by simulating harvest targets repeatedly (10 times) across a range of values. Once these targets were established, 25 simulations at the desired level of risk tolerance were generated to collect the mean and variances of the indicator variables. This number of simulations was chosen to capture as much of the range of variation as possible, while staying within reasonable computing times. Each 300-year simulation took approximately 25 min on a 2-GHz processor with 640 MB of RAM.

Results and discussion

Sustainable harvest target and risk

When harvesting is simulated without disturbance, an even-flow harvest target of approximately 3 million m^3 per decade can be maintained. The probability of failing to sustain a range of harvest targets when disturbance is included is shown by the logistic regression in Fig. 3. The sustainable harvest rates at our chosen risk tolerance (0.1) for both disturbance scenarios are identified in Figs. 3a and 3b. The resulting harvest flows from each of three scenarios are shown in Fig. 4.

Figure 5 shows that including historical rates of fire disturbance reduces harvest flows by 53%–58% in the three regimes with the highest rates of disturbance (Boreal Plains Upland, Boreal Foothills Valley, Boreal Foothills Mountain), while the reduction in the Wet Mountain regime was only 11%. Under the suppression scenario, a 2% increase in harvest relative to the historical disturbance scenario occurred in the Wet Mountain regime; however, the other regimes increased by 42%–55%. The Boreal Plains regime is the most sensitive to fire disturbance. It also experiences the largest number of escape events (approximately 8% of events) and therefore responds less to suppression than the Boreal Foothills Valley and Boreal Foothills Mountain regimes, where less than 1% of events escape. The Wet Mountain regime has relatively little disturbance, and the three scenarios produce similar harvest flows from this NDU.

Harvestable stock

Harvestable stock for each scenario is shown in Fig. 4. Without disturbance, harvestable stock declines steadily over the first 100 years (after an initial peak in the second decade that is related to fewer adjacency conflicts), until it is drawn down to levels that are close to the harvest rate (Fig. 4a). In the disturbance scenarios, harvestable stock is also initially drawn down, although the average value always remains higher than the harvest target (Figs. 4b and 4c). Because the harvestable stock is higher than the harvest, on average, there is a buffer present on the landscape that provides some insurance against fire disturbance. This buffer also has a

Fig. 6. Projected late-seral area.
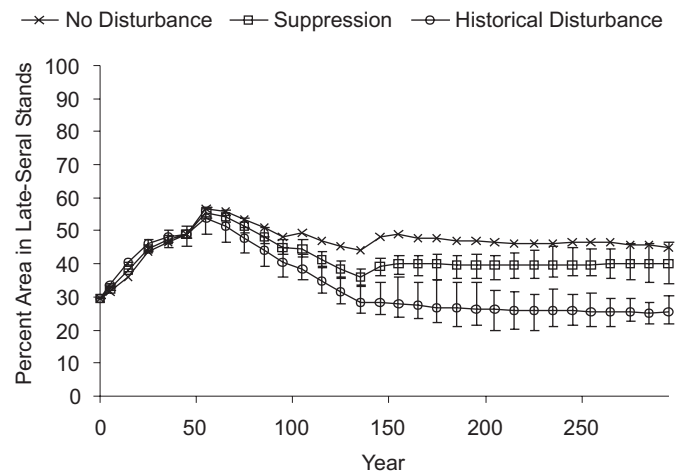
range of variation, and its lower bound is close to the sustainable rate of harvest. The lower bound of harvestable stock occasionally drops below the harvest rate, indicating the presence of occasional shortfalls in timber supply, and the frequency of these shortfalls reflects the risk of achieving the sustainable harvest target (Fig. 3).

Late-seral area

Figure 6 shows projections for the percentage of late-seral area for each scenario. The percentage of late-seral area increases in all scenarios for the first 60 years, followed by a decline as harvesting and disturbance progressively draw down the amount of old forest on the landscape. Under the historical disturbance scenario, the percentage of late-seral area stabilizes at an average of approximately 26% after 200 years, although this amount ranges from 20% to 32%. Under the suppressed disturbance and no-disturbance scenarios, the percentage of late-seral area stabilizes at higher average levels after 200 years (approximately 40% and 45%, respectively).

The average values and the range of variation of the percentage of late-seral area for the last 100 years of each scenario are summarized in Fig. 7. The larger amounts of old-seral area in the suppressed disturbance and no-disturbance scenarios are largely due to an accumulation of old stands in the nontimber harvest landbase (Fig. 7a). On the timber harvest landbase, the percentage of late-seral area changes less between scenarios (Fig. 7b) because harvests can increase when disturbance decreases, and this tends to offset potential gains in late-seral area expected when there is less disturbance.

Profit

Projected profit flows for each scenario are shown in Fig. 8. All three scenarios show a large increase in profit after the first decade, which has the highest road development costs. The average profit of $78 million per decade in the no-disturbance scenario and $37 million per decade under the historical disturbance scenario indicate that disturbance caused a loss in profit of approximately $41 million per decade, or approximately $4 million per year. With the introduction of suppression, harvest rates and profits increased

Fig. 7. Average percentage of late-seral area for all scenarios (years 200–300) for (*a*) the nontimber harvest landbase (NTHLB) and (*b*) the timber harvest landbase (THLB).
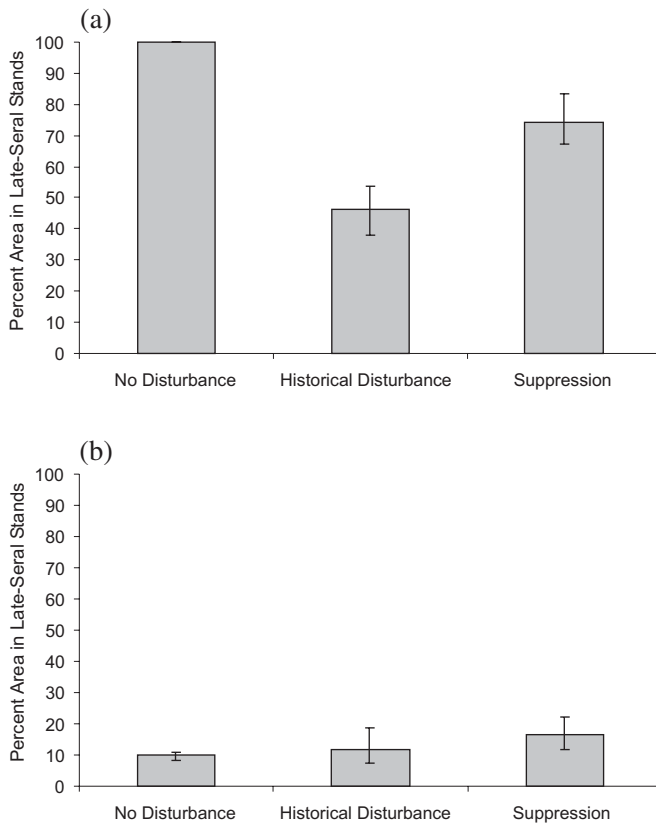
relative to those under the historical disturbance scenario. Costs associated with the suppression activities themselves (i.e., prevention, patrols, initial attack, and mop-up) are not included in our calculations, but the differences in profit provide an estimate of the value of suppression activities. With suppression, an average profit of $55 million per decade was observed, which is an increase of approximately $1.8 million per year relative to the historical disturbance scenario. The net present value for each scenario is also shown in Fig. 8. Historical rates of natural disturbance reduced the net present value from approximately $181 million to $74 million. The suppression scenario increased net present value to $115 million, which is approximately a 50% increase relative to values under the historical disturbance scenario.

Profit under different levels of risk tolerance: suppression scenario

Figure 9 shows profit for different levels of risk tolerance under the suppression scenario. As risk tolerance is increased, profits rise to higher levels over the first 75 years, but become volatile later on as buffer stocks are drawn down to levels that cannot absorb disturbance activity. In the last 150 years of the simulations, harvesting at a 0.1 risk tolerance delivers the most stable long-term profitability at $55 million per decade, along with minimums of $50 million and peaks of just under $60 million. Increasing risk tolerance to 0.5 increases long-term profitability to approximately

$56.5 million, although occasional drops in profit occur, falling to as low as $45 million. Using a risk tolerance of 0.9, average long-term profits are $58 million; however, drops in profit become more frequent. Discounting favours profits generated in the short term over those generated in the long term, so we observe that increasing risk tolerance results in higher net present value (assuming a constant discount rate for all risk tolerances).

General discussion

Scale is an important factor when evaluating sustainability. Smaller landscapes are more vulnerable to catastrophic losses, which can lead to highly constrained harvest targets. With larger planning units, flexibility exists to shift harvests elsewhere while disturbed areas recover. Time is the other important scale, and even large landscapes are subject to catastrophic losses provided a sufficiently long time scale is considered. For these reasons, our tolerance for the periodic impacts of catastrophic events must be carefully evaluated. Using a logistic model to estimate risk provided an effective approach to estimating harvest targets in our study. Although we used harvest volume as a basis for quantifying risk, the same methods could also be applied to other indicators of sustainability such as profit, critical levels of habitat (e.g., old seral), or other nontimber values.

Our harvest targets approximate the minimum level of harvestable stock encountered through simulations. When disturbance is not included and harvest rates are maximized, harvestable stock is typically drawn down to levels that are at or near the harvest rate. When stochastic disturbance is introduced and harvesting is reduced to sustainable levels, harvestable stock stays higher than the harvest rate (on average), indicating that a buffer is typically present. However, it is important to recognize the range of variation and periodic absence of buffers following peaks in disturbance. While landscape attributes such as late-seral area may increase as buffers accumulate, they can still be drastically reduced by occasional catastrophic events. Since it is common for harvest constraints to be relaxed during salvage operations that follow major fires, we could use mature growing stock on the timber harvest landbase to approximate the harvestable stock. Mature growing stock is more easily calculated than the harvestable stock, and this would reduce computing time in our model.

Since different parts of a landscape can have different disturbance characteristics, harvest flows from each disturbance regime will reflect these characteristics. By explicitly modelling disturbance on landscapes, a better understanding is gained of the long-term supply profile of the forest. Salvage harvesting was an important component in our model, allowing shortfalls that result from peak disturbance periods to be made up by the removal of damaged timber. In the current model, disturbed stands are only salvaged until the harvest target for the period is met, potentially leaving large areas of salvageable timber underutilized. If this limit were relaxed, peaks in harvestable stock resulting from disturbance could be utilized more efficiently and provide more managed stand areas with higher growth rates and hence higher sustainable harvest rates.

Our method of simulating disturbance, where event occurrence and event size are generated from empirical distribu-

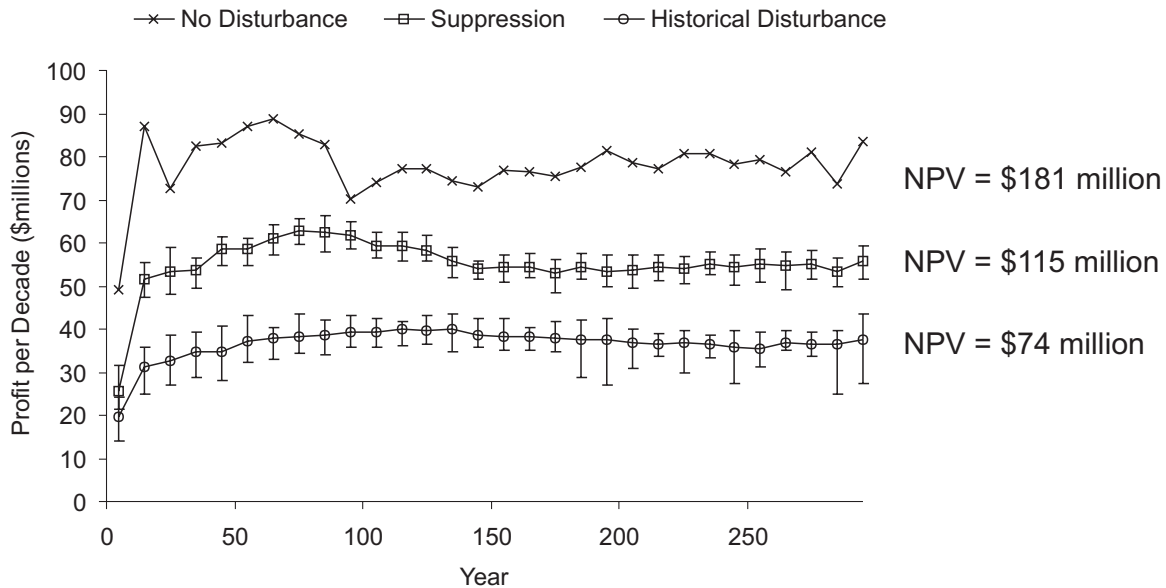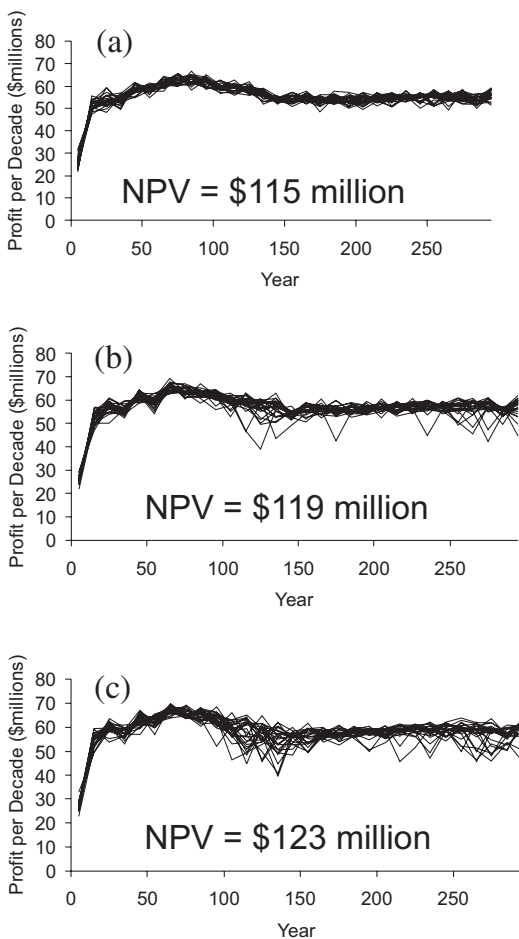**Fig. 8.** Projected average profit per decade for scenarios.

Fig. 9. Profit per decade and average net present value from 25 simulations of harvesting and suppression at three levels of risk: (*a*) 0.1, (*b*) 0.5, and (*c*) 0.9.

tions, works well where disturbance regimes are classified into large contiguous areas such as whole watersheds or on south–north aspects. Where regimes are dispersed, more

complex models of disturbance that consider individual stand conditions and event behavior will be required. We have also assumed consistent fire occurrence patterns through time; however, historical rates of fire disturbance have varied through time (Steventon 1997), and climate change has the potential to increase fire occurrence (Hirsch 2003). It is also commonly believed that fire suppression simply delays the onset of fires, which may materialize into larger catastrophic events than those observed under historical conditions. Issues such as these leave room for further research and could be explored in the modelling environment developed here.

Another important consideration is the number of simulations used in the scenarios. We chose a number of simulations that we felt provided reasonable estimates of the variation in fire disturbance which could be accomplished within acceptable computing time. More simulations will produce better estimates of the range of possible outcomes, thus giving managers and other interested parties better information for decision-making. This trade-off between precision and computing time is specific to each forest and to the decision-makers. Processing times for our models could be improved with advanced programming and the choice of indicators (e.g., mature growing stock instead of harvestable stock), thus allowing for more simulations to be run per scenario. This would provide information on how the range of variation changes according to the number of simulations.

Conclusions

Although timing, location, and extent of individual fires will always be uncertain, modelling provides insight into how these events might cumulatively impact harvests and landscape conditions. The inclusion of profit, as done here, can be used to guide investment decisions for timber processing facilities or to evaluate fire suppression policy. Likewise, tracking the amount of old-seral area provides insight into forest structure that is likely to result from disturbance events. While we only used the risk tolerance approach to

setting harvest targets, this method could also be applied to profitability, the amount of old-seral forest, or the amount of other important habitat types.

Opportunities for further research within this modelling framework remain. These include testing different assumptions about rare catastrophic events, relationships between stand age and fire occurrence, burn rates within different stand types, gamma parameters, correlations between fire rates and the size of disturbance, and improved representations of suppression. The spatial and temporal scales at which we incorporate the effect of fire on sustainability are additional questions, requiring consideration of both ecosystem processes and social factors. Exploring the risk associated with different scenarios is important whenever natural disturbance is a significant driver of forest ecosystems, and strategies can be chosen that are resilient to future events and yet do not overly constrain us based on unlikely worst-case scenarios.

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