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Emulating natural disturbances as a forest management goal: Lessons from fire regime simulations

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ABSTRACT

Emulating natural forest disturbance is an increasingly popular forest management paradigm that is considered a means of achieving forest sustainability. Adopting this goal requires a sound understanding of natural disturbances at scales that correspond to management policies and strategies. In boreal forest landscapes driven by periodic stand-replacing fires this requires knowledge of fire regime characteristics, especially their spatial and temporal variability as well as stochasticity. The major goal of this study was to demonstrate the utility of fire regime simulation modeling to explore the variability of fire regime characteristics, with respect to formulating and assessing forest management strategies. We conducted a modeling experiment in a boreal forest landscape of northwestern Ontario, Canada, to examine its long-term fire regime in relation to forest policies on harvest size distribution. We used BFOLDS, a spatially explicit fire regime model that simulates individual fire events mechanistically in response to fire weather, fuel patterns, and terrain. The fire regimes in four large eco-regions were modeled for a 200-year period under three fire-weather (cold, normal, and warm) scenarios, with replications. We found that fire size distribution in all eco-regions followed power law under all weather scenarios, but their slopes and intercepts varied among eco-regions and fire weather scenarios. Warming fire weather increased burn rates and fire numbers in all eco-regions, albeit to different degrees. Overall, the variability among eco-regions was higher than the variability among fire weather scenarios, and among replicates. Comparisons of simulated fire size classes with those from an 86-year long fire history showed that empirical data cannot capture the variability that could be revealed by simulation modeling. We also show that fire size distribution is spatially heterogeneous within eco-regions, and provide several suggestions for forest policy directions with respect to forest harvest size distributions and harvest rates, based on the variability of fire regime characteristics. An assessment of present forest policies of emulating natural disturbances that guide forest harvest sizes showed that these are incongruent with simulated fire size distributions under all scenarios with one exception. Overall, this study illustrates the value of scenario simulation modeling to explore and quantify the variability of forest fire regime, for use in forest policies and strategies that attempt to emulate natural disturbance.

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1. Introduction

Ecological perspective is an important component of forest sustainability, where forest management goals, approaches, strategies, and practices are designed to address the sustained functioning of ecosystems at multiple scales (Hunter, 1993). Given the absence of perfect information about ecosystem patterns and processes at all ecological scales, which would be required to engineer management designs that ensure ecological sustainability, an alternative approach has evolved during the last two decades. This approach, emulating natural forest disturbances, is

considered a surrogate for ensuring sustainability in forest management and a coarse filter for conserving biodiversity (Hunter, 1990; Attiwill, 1994). Its premise is simple and assumes that (a) forest ecosystems have evolved under natural disturbance regimes (e.g., forest fires) making them resilient to periodic occurrence of those disturbances and (b) maintaining human intervention regimes (e.g., forest harvest) within the limits of the natural disturbance regimes ensures sustained functioning of those ecosystems (Niemela, 1999; Perera and Buse, 2004). While the specific applications of this principle vary, it provides an effective benchmark or a null hypothesis to design and assess forest management practices (Perera and Buse, 2004). In regions where fire disturbances are common, this forest management paradigm has gained particular popularity both in research (e.g., Bergeron and Harvey, 1997; McRae et al., 2001; Romme et al.,

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2004; Gauthier et al., 2004; Wimberly et al., 2004) and policies (OMNR, 2001; ASRD, 2006; Jetté, 2007).

A crucial need for the pursuit of emulating natural forest disturbances as a management goal, whether at stand- or landscape-scale, is adequate knowledge of natural disturbances at appropriate scales (Perera et al., 2004a). When policies are formulated and subsequent management strategies are designed at landscape-scale, the appropriate knowledge requirement is *fire regime*-level information (as opposed to fire event-level information), which generalizes spatio-temporal patterns of individual fire events for large areas over long periods. Many indicators have been used in literature to describe natural disturbance regimes, addressing their temporal and spatial aspects as well as impact (White and Pickett, 1985), which may be used as emulation criteria in designing forest management strategies for natural disturbance emulation. Specific fire regime characteristics such as annual burn rate, fire return interval, and fire size distribution, as well as subsequent landscape age composition and land cover patterns have parallels in forest harvest regimes. For example, mean annual burn rates could be considered templates for designing mean annual harvest rates, and the fire return intervals could provide benchmarks for designing forest harvest rotation periods (Perera and Buse, 2004).

Natural fire regimes are highly heterogeneous, which is associated with time and space as well as having stochasticity within a given time and space (Lertzman et al., 1998). This variability results from a multitude of factors that directly affect fire regimes, and through their complex interactions, render regime characterizations difficult (Cui and Perera, 2008). In spite of their popular appeal, empirical methods of characterizing fire regimes using historical data do not completely capture their natural variability (Suffling and Perera, 2004), because even if the data are precise, complete, and centuries-long, this historical information provides just one temporal series of many possible realizations. Scenario simulations provide an alternative, where natural fire regimes may be simulated using quantitative models that embody both mechanistic and empirical knowledge of fire processes under many assumptions of fire weather, land cover, and human interventions. As well, by incorporating stochasticity associated with fire processes, simulation modeling permits the exploration of many possible if-then scenarios, and in sum, offers a broader portrayal of the sample space of fire regime characteristics (Perera et al., 2004b).

Fire size distribution, which describes the variability of the extent of individual fires synoptically, is a characteristic that has been commonly used to typify fire regimes (Cui and Perera, 2008). Spatially explicit simulations of fire size distributions are also useful in designing forest harvest schemes (e.g., Martell, 1994). The temporal and spatial variability of fire size distribution, as well as spatial probability of incidence of fires of different sizes, can be used as emulation criteria in designing size-class distributions of forest harvest patches and spatial distribution of those harvest patches, while accounting for regional geo-climatic differences (Perera et al., 2004b). Furthermore, fire size distributions can also inform wildlife habitat supply (e.g., Fisher and Wilkinson, 2005), conservation area design (e.g. Baker, 1989), and regional land use planning (e.g., Romme et al., 2004).

In the above context, our broader goal here is to demonstrate the use of a spatially explicit stochastic simulation modeling approach to inform natural disturbance emulation strategies using a case study from the Canadian province of Ontario. It was among the first jurisdictions to legislate emulating natural forest disturbances as a sustainable forest management paradigm (Statutes of Ontario, 1995) and formulate a policy to address emulating natural fire disturbance patterns during forest management planning (OMNR, 2001). In the fire-driven boreal region of

Ontario's managed forest landscape, which encompasses over 300,000 km², this policy guides the harvest patch size distribution to emulate size distribution of stand-replacing natural fires. Our specific objective was to simulate forest fire regimes of boreal Ontario under different scenarios of long-term fire weather (to represent hypothetical cold, normal, and warm trends) and examine the resulting fire size distribution, especially with respect to its variability both among- and within eco-regions. We do so with a view of informing the forest policy that attempts to emulate fire size distributions by guiding forest harvest size distribution in this boreal landscape.

2. Methods

2.1. Study area

The area we selected for the simulation study, the western part of Ontario, is a typical boreal forest landscape, composed of a shifting mosaic of forest cover patterns driven primarily by a large scale fire regime. As Fig. 1 illustrates, this area is burned extensively and frequently, and its recent fire history is well documented by a fire atlas (Perera et al., 1998). Forest management activities are also very common in this area, with increased rates of forest harvest since the 1950s (Perera and Baldwin, 2000). This area is characterized by cold-dry climate, well drained soil and rolling terrain interspersed with lakes, and dominated by dense conifer and mixed-conifer forest (Rowe, 1972). Geologically, it is considered predominantly boreal shield, and sub-divided into eco-regions based on local geo-climatic variability (Hills, 1959). These eco-regions, 3W, 3S, 4W, and 4S, are large, ranging from 2,172,306 ha (4W) to 10,132,317 ha (3W) (Fig. 1), and have been used as surrogate units for strategic land use planning for conservation and forest harvest. Detailed and cartographic descriptions of the physical geography, climate, vegetation, fire history, and harvest history of this area are described in Perera et al. (2000).

2.2. Simulation model

We used the Boreal Forest Landscape Dynamics Simulator (BFOLDS) to model the fire regime of the study area. BFOLDS is a spatially explicit hybrid simulation model, consisting of a process-based fire event simulation module and an empirical-based forest succession simulation module (Perera et al., 2008). As well, it is a stochastic simulation model, designed to capture the probabilities associated with sub-processes of fire regimes such as fire ignition, fire event extinguishment, forest cover transition and subsequent fuel availability. Using a raster-based fire growth module founded on the principles of the Canadian Fire Behavior Prediction system (Forestry Canada Fire Danger Group, 1992), BFOLDS simulates multiple fire events on a given landscape at 1-ha resolution and daily intervals, using spatial data on fuel types, weather, and topography.

BFOLDS assumes the number of successful ignitions for any simulation day follows a filtered Poisson process, with its mean derived from the daily ignition data of fire weather input. For example, if the number of ignitions of a fire weather day is m , the number m is used as a mean to draw a number n from a probability distribution (Poisson if $m < 30$, otherwise normal), and the number of ignitions seeded for that simulation day will be n . These ignition points may be positioned within a simulation landscape either randomly or with spatial biases as a user assumption. Seeded ignitions will succeed only if the fuel moisture at the location is below a threshold value. Fuel moisture is indicated by the Duff Moisture Code, a Canadian fire weather index that defines a numeric rating of the average moisture content of loosely

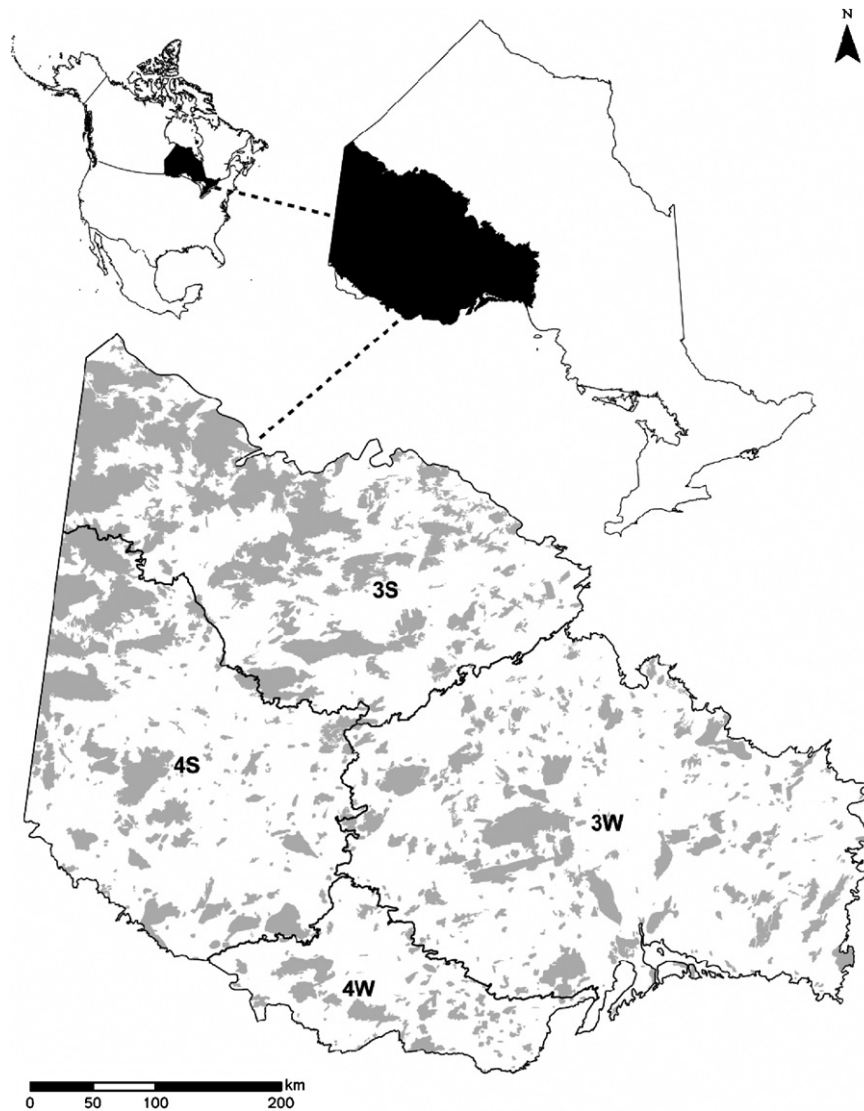


Fig. 1. The northwestern Ontario study area, with its four eco-regions 3W, 4W, 4S, and 3S. Light gray shading depicts the area burned by wildfires during 1921–2005.

compacted fuel (Forestry Canada Fire Danger Group, 1992). Once a fire is ignited in a cell, it can spread to 32 neighboring cells in a nine by nine cell window. The spread time to neighboring cells is calculated using Canadian Fire Behavior Prediction system based on prevailing weather conditions and the fuel types in those cells. Fire spread stops when fuel moisture values rise above a threshold, which is set by the user based on local knowledge. When all cells within a fire perimeter stop their fire spread, the whole fire is considered extinguished. BFOLDS thus simulates ignition, spread, and extinguishment of multiple fires simultaneously in a large landscape, guided by streams of daily fire weather during a fire season, and based on spatial distribution of fuel types.

The long-term forest succession in BFOLDS is stochastically simulated at 1 ha resolution, based on a time-dependent Markov chain, using spatial data on forest cover composition, forest cover age, terrain, and soil. Further details of BFOLDS model can be found in Perera et al. (2008) and at <http://www.fire-regime-model.com/>.

Because BFOLDS generates fire events mechanistically, rather than sub-sampling historical or other empirical distributions of fire regime information, the simulated fire regimes characteristics are entirely an emergent property of the model function (a combination of model logic, input data, and various *a priori* assumptions). Therefore, BFOLDS is essentially an exploratory model that is well

suited for investigations of what-if scenarios of weather and land cover, and subsequent examinations of spatio-temporal variability of boreal forest landscape characteristics, for example, spatial potential of old growth forest occurrence (Perera et al., 2003), spatial fire regime (Perera et al., 2004b), effects of climate change on land use planning (Munoz-Marquez, 2005), and songbird habitat patterns under different forest cover (Rempel et al., 2007). This model has also been applied in developing new forest policy guidelines (<http://www.mnr.gov.on.ca/en/Business/Forests/>), as well as assessing the effectiveness of present policy guidelines for forest landscape management (Perera et al., 2009).

2.3. Simulation scenarios

The fire regimes of the four eco-regions of the study area were simulated separately, using the present-day land covers of respective eco-regions as their initial states. These land cover would change with time during simulations due to forest cover transitions caused by fire disturbances and due to ageing in the absence of disturbance. Length of the simulated fire regime was 200 years, where each fire event that occurred within the eco-regions was tracked by its location and time, which permitted assemblage of many spatio-temporal summaries. Given our

objective of exploring potential variability of fire regime, we assumed three different fire-weather scenarios during simulations as surrogates of potential climate change.

The three simulation scenarios of fire weather (cold, normal, and warm) were constructed from 42 years (1963–2004) of daily fire weather (temperature, relative humidity, wind, and rainfall) records from weather stations within the eco-regions. The *normal* scenario assumes that the fire weather during the 200-year simulation period does not exceed the range of annual variability that prevailed during that 42-year period. Each weather year was randomly selected based on probability p . For the *normal* scenario, $p = 1/42$. We then ranked the annual area burn rates for the 42 years, and selected the 8 years with highest burn rates as the “warmest” years (Eight weather years were selected following Pareto principle of 80:20, where 20% of the warmest weather years burned approximately 80% of the total area during the 42 years, and 20% of 42 is 8). For the *cold* scenario, we assumed that the probability of occurrence of those warmest years p_w is half the probability of the other 34 years, p . Because $p_w = 0.5p$ and $34p + 8p_w = 1$ we have $p = 1/38$ and $p_w = 1/76$. Similarly, for the *warm* scenario, we assumed that the probability of occurrence of the warmest years p_w is twice the probability of the other 34 years, p . Because $p_w = 2p$ and $34p + 8p_w = 1$, we have $p_w = 1/50$ and $p = 1/25$. To preserve their temporal autocorrelations, we did not alter sub-annual trends, the daily fire weather patterns within years, or hourly fire weather patterns within days.

To account for the uncertainty of knowledge of spatial patterns of lightning-caused fire ignitions, we assumed fire ignitions within eco-regions could be either random or spatially biased to patterns that prevailed in the recorded history. Thus, the seeding of fire ignitions within eco-regions were mixed: for half of the replicates within each treatment combination, ignitions were spatially biased to lightning-ignitions that occurred during the last 42 years (see <http://www.fire-regime-model.com/> for details of the biasing technique), and the other half were seeded randomly in space. When analyzing simulated data we combined the results from two lightning patterns to simplify the results presented here.

We also assumed that once a 1-ha pixel is burned, its forest cover is destroyed entirely, and such a pixel cannot reburn within 10 years. To allow fires that could originate from outside but spread into the study areas, we expanded the four eco-regions by imposing 20 km wide external buffers. The extents of fires within the buffers were eliminated from the data analyses, regardless of their origin (study area or the buffer). All fires that ignited in the buffer but did not spread into the study area were not counted. Overall, we had 720 simulation runs; 60 replicates for each eco-region–fire weather scenario combination (4×3). All simulations were conducted at 1 ha resolution, with fire event data recorded annually.

2.4. Simulation input data

The air photo-based Forest Resources Inventory of Ontario (OMNR, 2000) was used as the basis for forest cover data used in BFOLDS simulations. The forest cover types of the respective eco-regions were translated to fuel types using the classification scheme of Forestry Canada Fire Danger Group (1992) and Taylor et al. (1988). Daily data on temperature, relative humidity, wind, and rainfall was collected from weather stations within the eco-regions and interpolated using a cubic spline algorithm (Flannigan and Wotton, 1989). The forest cover types and their present ages were used as the year-zero state to seed subsequent forest succession processes. The terrain information (slope and aspect), which influences fire spread, were extracted from DTED digital elevation model at 1 ha spatial resolution (<http://geobase.ca>). Table 1 provides a summary of all data sources used in the simulation study.

Table 1

BFOLDS model input and sources of data used in the fire regime simulation study.

Model input	Spatial database
Forest cover types Forest cover ages Fuel types	1:20,000 Forest Resources Inventory of Ontario (OMNR, 2000)
Fine fuel moisture code Duff moisture code Drought code Initial spread index Buildup index Fire ignitions	Daily weather data from multiple weather stations for 1963–2004 (point data) from OMNR historical fire weather archive
Slope Aspect	DTED digital elevation model (100 m) from http://geobase.ca
Soil moisture Soil nutrient	1:250,000 Ontario Land Inventory OMNR (1977)

All data were input as 1-ha raster surfaces.

3. Results

3.1. Overall fire regime

While many other aspects of fire regime can be characterized from the results of the simulation modeling exercise, here we focus mainly on the fire sizes and their probability distribution. This information was constructed from the individual fires that occurred annually within the 200-year simulation period for each of the 720 simulation runs.

The annual burn rate (mean annual area burned during 200 years as a percentage of the total forested area in an eco-region) varied between 0.107% and 6.571% across all simulations. The highest burn rates were found in eco-region 4S, which far exceeded those of all other eco-regions (Fig. 2a). Within all eco-regions, the warm fire weather produced higher burn rates than the normal fire weather, and the normal fire weather higher rates than the cold, with their differences exceeding the 95% confidence intervals. However, warming weather increased the burn rates most markedly in 4S compared to other eco-regions. Mean fire density (number of fires over a 200-year period, per million ha) varied from 1068 to 3756 across all simulations. Eco-region 4W had the highest fire density and 3W the lowest, with the warm weather producing more fires in all eco-regions (Fig. 2b). The progressively warming weather scenarios had the most pronounced effect of increasing mean fire density in eco-region 4W, and the least in 4S.

3.2. Fire size distribution

Fire regimes in all eco-regions were characterized by a high number of small fires. The fewest number of small fires was seen in simulation runs from the eco-region with the highest annual burn rate, 4S, where less than 25% of all fires (mean of 7891 across the three weather scenarios) were <1 ha. The eco-region 3W had a mean of >10,000 fires per 200 years, but more than 25% of those were <1 ha. In eco-regions 3S and 4W, which had mean fire numbers of 8997 and 4105, respectively, more than 50% of the fires were <1 ha.

The relationship between fire sizes and their frequency of occurrence can be synoptically expressed as a probability distribution of individual fire sizes to typify fire regime. As reviewed by Cui and Perera (2008), fire size distributions in boreal forest landscapes are expected to follow a power law distribution, where a great majority of fires are small, with most of the burn area resulting from a few large fires. As such, we fitted the model $\log(N) = \beta \log(A) + \alpha$, where N is the number of fires at a given size A , to all simulation scenarios. We did so without truncating fire

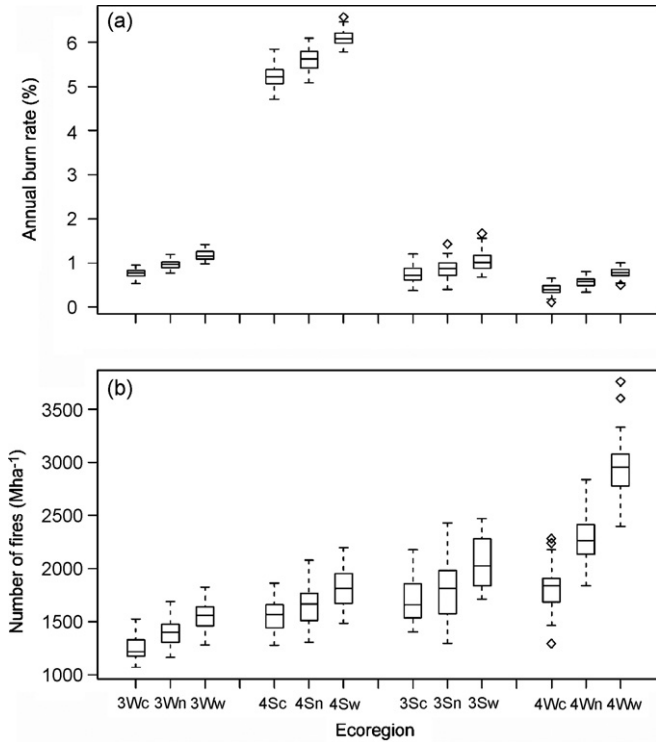


Fig. 2. Mean annual burn rates (a) and the mean fire density (b) from simulation runs for fire weather scenarios (c: cold, n: normal, w: warm) within the eco-regions 3W, 4S, 3S, and 4W. $N = 60$ for each box plot, where boxes indicate the interquartile range, middle lines the median, and whiskers the min–max values.

sizes to improve the fit of the log–log model. Power law distribution explained the fire size distribution in all simulation scenarios, with R^2 ranging from 0.437 to 0.598 (Table 2). All slope values were smaller than 1, indicating that though abundant, small

fires do not contribute significantly to the total area burned within each eco-region, and under all weather scenarios. Overall, smaller fires contribute to the total area burned the least in eco-region 4S and the most in 3W. Simulated fire weather scenarios produced mixed results among the eco-regions: Smaller fires burned relatively more area as the weather warmed in 4W, and to a lesser degree in 4S. In the other two eco-regions, both cold and normal fire weather scenarios resulted in relatively more area burned by small fires than did normal weather. The increase in total number of fires with warming fire weather was evident in the increased intercept values.

In Table 3 we summarize the fire sizes at the median, the 75th percentile, and the 90th percentile of all simulations for the three fire weather scenarios within each eco-region. Although 4S is the second largest eco-region, almost half the size of 3W, it had much larger fire sizes, well above the other eco-regions at the 50th, 75th and 90th percentiles. Eco-region 4W had the fewest large fires, and even at the 90th percentile its fire sizes were <1000 ha. Effect of fire weather on fire sizes was mixed among eco-regions. Fire weather did not affect simulated fire sizes at any percentile within 4S and 3S, as indicated by overlapping confidence intervals of their means. However, the warmer fire weather produced larger mean fire sizes in 3W (at all three percentiles) and 4W (at the 75th and 90th percentiles).

3.3. Fire size variability

We further examined the variability of the number of simulated fires within different size classes among the four eco-regions using six log-scale bins (<1 ha, $\geq 1-10$ ha, $>10-100$ ha, $>100-1000$ ha, $>1000-10,000$ ha, and $>10,000$ ha). Each bin had 60 values, one from each replicate simulation run, of the number of fires in that size-class. Results presented here are only for the normal weather scenario, to permit a ready comparison to an empirical data set of historical fires for the four eco-regions constructed from a fire atlas data set from 1920 to 1995 (Perera et al., 1998) and the on-going

Table 2
Log–log regression models fitted to simulated fire size distributions of eco-region–fire weather combinations (N is the number of fires at a given size A).

Eco-region	Regression models under weather scenarios (200-year simulation period; 60 replications per region–weather combination)		
	Cold	Normal	Warm
3W	$\log(N) = -0.392 \log(A) + 1.453, R^2 = 0.595$	$\log(N) = -0.389 \log(A) + 1.46, R^2 = 0.594$	$\log(N) = -0.391 \log(A) + 1.484, R^2 = 0.598$
4S	$\log(N) = -0.206 \log(A) + 0.840, R^2 = 0.437$	$\log(N) = -0.208 \log(A) + 0.851, R^2 = 0.434$	$\log(N) = -0.215 \log(A) + 0.883, R^2 = 0.435$
3S	$\log(N) = -0.247 \log(A) + 0.883, R^2 = 0.476$	$\log(N) = -0.240 \log(A) + 0.870, R^2 = 0.468$	$\log(N) = -0.247 \log(A) + 0.905, R^2 = 0.473$
4W	$\log(N) = -0.248 \log(A) + 0.811, R^2 = 0.454$	$\log(N) = -0.271 \log(A) + 0.909, R^2 = 0.476$	$\log(N) = -0.314 \log(A) + 1.077, R^2 = 0.525$

All slope values were statistically significant ($p = 0.05$).

Table 3
Overall summary of the fire regime simulation results from the four eco-regions in northwestern boreal Ontario.

Eco-region (forested area ha)	Simulated fire weather	Mean fire size (ha) at different percentiles of the simulated fire regime $\pm 95\%$ confidence interval ($N = 60$)		
		50th percentile	75th percentile	90th percentile
		3W (7,417,259 ha)	Cold Normal Warm	59 \pm 3 70 \pm 4 85 \pm 4
4S (4,722,436 ha)	Cold Normal Warm	912 \pm 36 978 \pm 54 917 \pm 46	6974 \pm 208 7127 \pm 247 6893 \pm 193	19520 \pm 527 19800 \pm 487 19491 \pm 441
3S (3,541,098 ha)	Cold Normal Warm	1 \pm 0 1 \pm 0 1 \pm 0	175 \pm 22 166 \pm 20 162 \pm 19	1955 \pm 122 1993 \pm 127 2004 \pm 111
4W (1,753,587 ha)	Cold Normal Warm	1 \pm 0 1 \pm 0 1 \pm 0	34 \pm 6 79 \pm 8 131 \pm 8	615 \pm 42 788 \pm 39 880 \pm 29

fire monitoring database of the Ontario Ministry of Natural Resources from 1996 to 2005. This data set has a size limit since the spatial records from 1920 to 1976 are available only for fires ≥ 200 ha. Therefore, we could group the historical fires into the three largest bins only. To account for the shorter observation period of the empirical data, we re-scaled the bin values by a factor of 2.33 (i.e., $200/86$). This size limitation and the differences in time period notwithstanding, the empirical data set may be viewed as an alternate replicate in this milieu.

Fig. 3 illustrates that the simulated fire number and their sizes is generally similar among the eco-regions 3W, 3S, and 4W. Although the absolute values were different, the smallest size class dominated the simulated fires in these three eco-regions, with the middle bin (>100 – 1000 ha) containing the highest fire number among the other size classes. In contrast, simulations in eco-region 4S produced far fewer small fires (<1 ha), and the mode was in the second largest (>1000 – $10,000$ ha) class. As well, in 4S the largest fires ($>10,000$ ha) were more abundant than the smallest (<1 ha). In most cases, the empirical data was outside or at the end of the range of the simulated results except in eco-region 4W. The number of larger fires (>1000 ha) in the empirical data matched those from the simulations in 4W. In general, the trend in empirical

data, albeit truncated, followed the simulated size classes in all eco-regions but 4S.

Forest fire regimes, particularly forest fire size distributions, are not spatially homogenous within eco-regions. This was captured in this study by a spatially explicit model and we were able to examine the variability of fire size distribution and burn probability in space. While there are several different ways to portray the spatial heterogeneity, we combined burn probability and modes of fire size in one map to demonstrate the possibility with a simple set of 2×2 classes. We arbitrarily (just to illustrate within-eco-region variability) used two fire-size class bins – large fires ($>10,000$ ha) and small fires ($\leq 10,000$ ha) and two burn probability bins – high probability (>0.16) and low probability (≤ 0.16). Below we illustrate (Fig. 4) an example of the resulting spatial heterogeneity of the probability of occurrence of different fire sizes in one eco-region (3W) under one fire weather scenario (normal).

Fig. 4 shows that certain parts of the eco-region are more likely to burn than others, and when they do burn the likelihood of those fires being large or small varies. This simple 2×2 matrix may be expanded to include many categories of burn probability and fire sizes to depict spatial variability of fire sizes to a required level of detail.

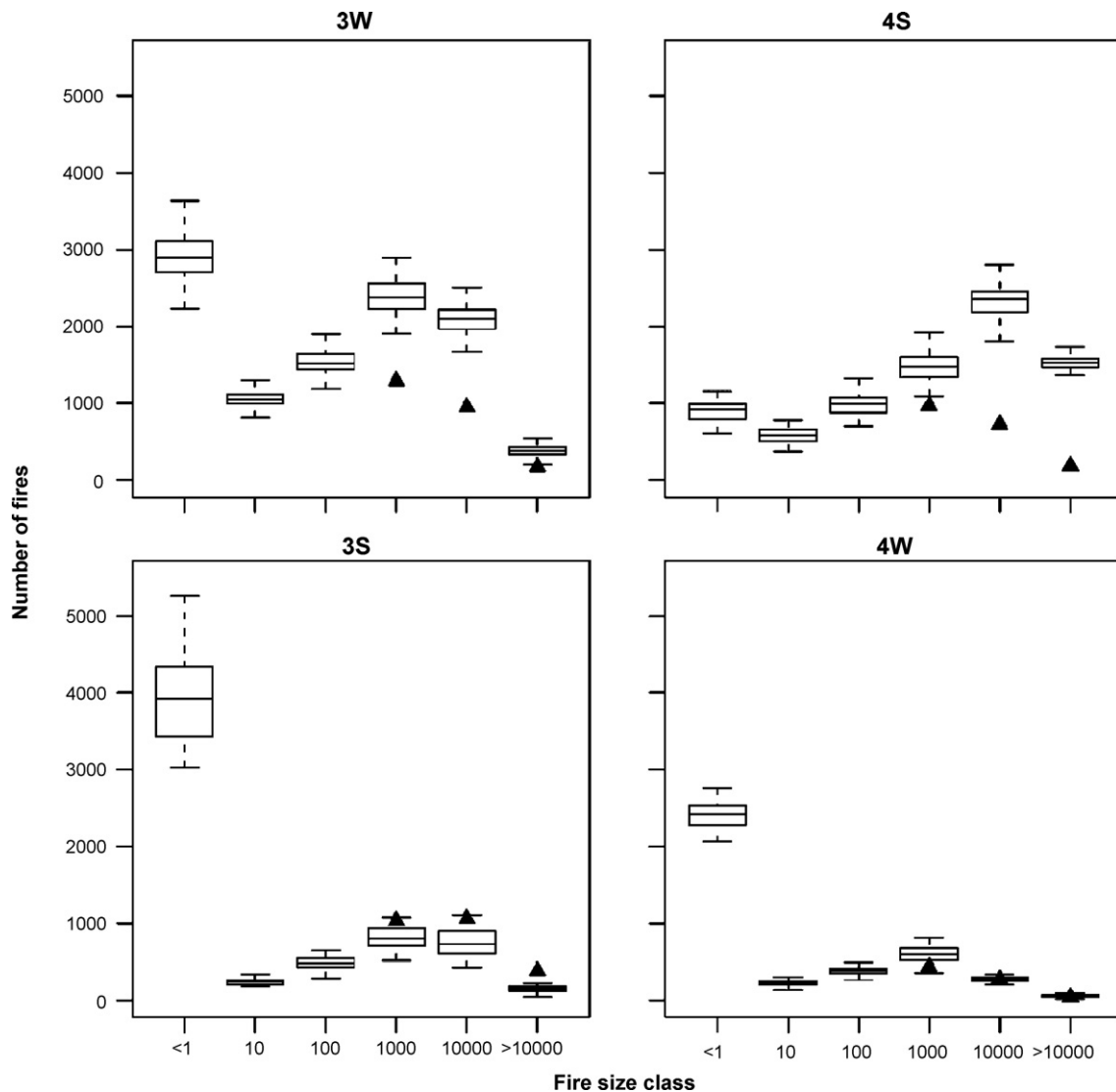


Fig. 3. Number of fires in different size classes from 200-year simulation runs for eco-regions 3W, 4S, 3S, and 4W for the normal weather scenario. $N = 60$ for each box plot, where boxes indicate the interquartile range, middle lines the median, and whiskers the min–max values. The dark triangles (\blacktriangle) represent empirical data (see text for details).

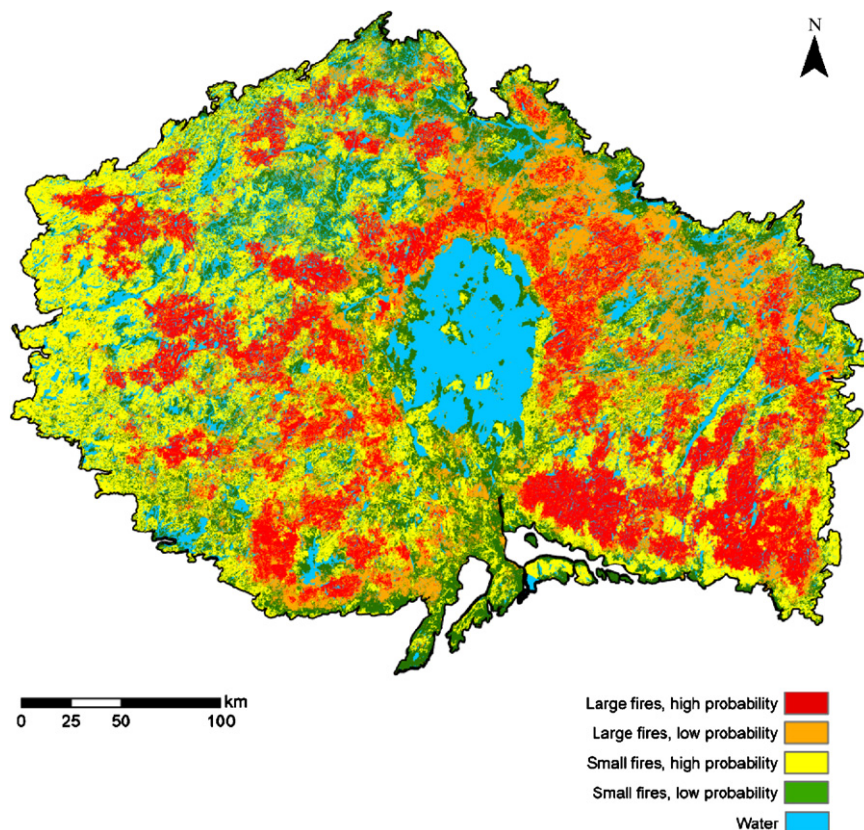


Fig. 4. Spatial variability in the probability of occurrence of simulated fire sizes within the eco-region 3W under the normal fire weather scenario (Large fires >10,000 ha, small fires ≤10,000 ha, high probability >0.16, low probability ≤0.16). Fires sizes and burn probabilities are estimated from 60 replicates of 200-year simulation runs.

4. Discussion

4.1. Simulated fire regime

This study focused on the major patterns of fire size distribution in northwestern Ontario, evident from the simulated results of the case study, to examine its utility for emulating natural disturbances by forest harvesting. First, specific properties of fire size distribution, their slopes and intercepts, as well as total number of fires, appeared to be unique to each eco-region. Simulated fire sizes of all eco-regions followed power law distribution, but not very strongly (with R^2 from 0.4 to 0.6). We cannot speculate on the relative weak fit of the power law distribution to simulated data because it could be due to knowledge uncertainty in modeling and/or because of the knowledge uncertainty of the fit of power law distribution as *the null model* for fire regimes of large regions and long periods. Most reports (see a review by Cui and Perera, 2006) that fit power law distribution to fire sizes are from considerably smaller study areas ($\approx 10^3$ ha) and shorter observation periods (few decades) than this study. Modeling studies we reviewed previously (Cui and Perera, 2006) also do not provide concrete evidence because these models use empirical assumptions of fire size distributions *a priori*. Second, in all cases of simulated results, the among-eco-regional variability exceeded the among-replicate variability and among-fire weather variability as seen in Table 3. Eco-region 4S had the most severe fire regime (highest burn rates, largest fire sizes) and 4W the mildest (lowest burn rates, smallest fire sizes). Third, fire size occurrence was spatially heterogeneous within eco-regions: fire size distribution, annual burn rates, burn probability, and many other fire regime indices varied spatially *within* an eco-region, with evidence of spatial biases, as shown in Fig. 4. Fourth, warming fire weather scenarios increased the number of fires, and shifted the fire size distribution higher,

resulting in higher annual burn rates in all eco-regions. However, the rate of increase varied among eco-regions: 4S had the highest rate of increase in annual burn rate and 4W the lowest; 4W had the highest rate of increase in fire density and 4S the lowest. A multitude of reasons may have caused the among-eco-regional differences in simulated burn rates and fire size distribution, ranging from input data differences among-eco-regions (for example in patterns of fuel, forest succession, and ignition to fire weather) as well as emerging properties of model functions such as self-organization of fire events in space. Therefore, it is difficult to ascribe simple reasons, or to propose ecological hypotheses for the eco-regional differences because our modeling exercise was not specifically designed to isolate such causal factors.

4.2. Implications for developing and assessing forest management strategies

Patterns seen in simulations of fire size distributions can inform development of new forest management strategies with the goal of emulating natural disturbances, as well as provide a basis for revising present policies. In Table 4 we present a brief summary of lessons for developing new forest policies that emulate natural disturbance *sensu stricto* ecologically. We stress that the purpose here is not advocacy, and our results must be considered strictly in the context of model and scenario assumptions and as well as the simulation framework. The overall message here is that it is possible to capture the variability in fire sizes of the natural fire regime of a large region to aid in the design of forest harvest strategies.

Furthermore, we used the simulation results of this case study to examine the directions for emulating natural disturbances in the present forest policy (OMNR, 2001). For fire-driven boreal Ontario, this policy specifies that 80% of the forest harvest patches must be

Table 4

Examples of generalized lessons from simulated fire regime in northwestern Ontario and their implications for developing forest policies.

Fire regime characteristic	Forest policy direction
Fire size distribution is unique to eco-regions	Eco-region specific directions for forest harvest size distribution
Fire size distribution is power law	Many forest harvest patches must be very small, with progressive decrease in the number of larger patch sizes
Higher annual burn rate in eco-region 4S than others	Higher annual rates of forest harvest possible in eco-region 4S than others
Higher probability of large fire sizes in eco-region 4S than others	Larger forest harvest patch sizes possible in eco-region 4S than others
Fire size occurrence within eco-regions is not spatially homogenous	Spatial biases in locating forest harvest patches of different sizes within eco-regions

These insights must be considered strictly within the context of the simulation modeling exercise, and the confines of model and scenario assumptions (see Section 2 for details).

less than 260 ha following the Pareto principle of 80:20. This direction was not congruent with the variability observed in the simulation exercise. Simulated fire size variability that occurred among eco-regions, among fire weather scenarios, and among replicates exceeded this direction, with one exception. The policy direction was different from simulated fire sizes by a wide margin for eco-regions 3W and 4S and a narrower margin for 3S under all weather scenarios. In those eco-regions, 260 ha-fire size occurred at lower percentiles than the 80th (Fig. 5a). Also, the 80th percentiles of simulated fires in these eco-regions were at much large fire sizes (Fig. 5b). Simulated fires in 4W, under both cold and normal weather scenarios, were smaller than the policy direction: the 260 ha size was at a higher percentile and the fire sizes at 80th percentile were smaller. As Fig. 5 shows, the only simulated scenario that matched the policy direction was eco-region 4W under warm fire weather. These results show the necessity for eco-regional specific directions to account for spatial variability among eco-regions as well as variability that may occur due to possible context changes such as fire weather. As well, if these forest

policies are revised, they could use the eco-regionally specific fire size distributions and their variability as a guide while acknowledging the non-linearity of fire size distributions explicitly. Because the fire size distributions in all eco-regions are power law, the fire sizes change exponentially with percentile values. For example, if policies on forest harvest size distribution are revised using fire size distributions as a guide, a linear change in threshold percentile values may result in vastly different ranges in corresponding fire size threshold values. Moreover, the information on spatial variability and biases of fire sizes within eco-regions could be used as an ecological guide for spatially allocating forest harvest sizes.

4.3. Simulation results and empirical data of fire history

As shown earlier in Fig. 3, re-scaled empirical data of fire history was outside the interquartile range of simulated results in all eco-regions except 4W. Many mechanistic reasons for this incongruence are plausible. It is possible that simulated scenarios of what is possible and 'real' data from a period in history did not agree because the historical patterns in species and fuel composition are different from those used in simulations or because historical fires occurred amidst anthropogenic influences such as fire suppression and forest harvesting, which were not included in simulations. It is also probable that the simulation results are incorrect, due to flawed model assumptions and/or user assumptions and errors in input data. This is a distinct possibility because the scientific knowledge is full of uncertainties, and the input data usually are approximations of reality. Further and directed investigations are needed to isolate reasons for differences between simulated and empirical results.

Furthermore, we argue that direct comparisons between an empirical data set and simulated results do not necessarily elucidate the 'truth': if the historical data fall within the range of simulated results (for example 4W) it does not indicate that simulation model mechanisms or its results are valid or believable; and if they fall outside the range (for example 4S), that the converse is true. This is because historical data, however real or compelling they are, do not have replicates (as in designed experiments), and thus represent just one observation point of many possible outcomes of a stochastic process such as forest fire. The implicit assumption that one historical observation represents the most probable of all real events that could occur (i.e., the mean of all probable events) is questionable, and even if it happens to be correct, estimates of its probability distribution parameters (e.g., variance) are not known. Therefore, we assert that comparisons of one historical observation of a stochastic process with simulation results may be not informative because it is the statistical equivalent of comparing one random variable of unknown population parameters to a population of known parameters. Fig. 6 illustrates this point by a Venn diagram where both simulated fire regime results and the empirical observation of fire history are nested within the domain of all possible fire regimes. Because the probability distribution of all possible fire regimes is

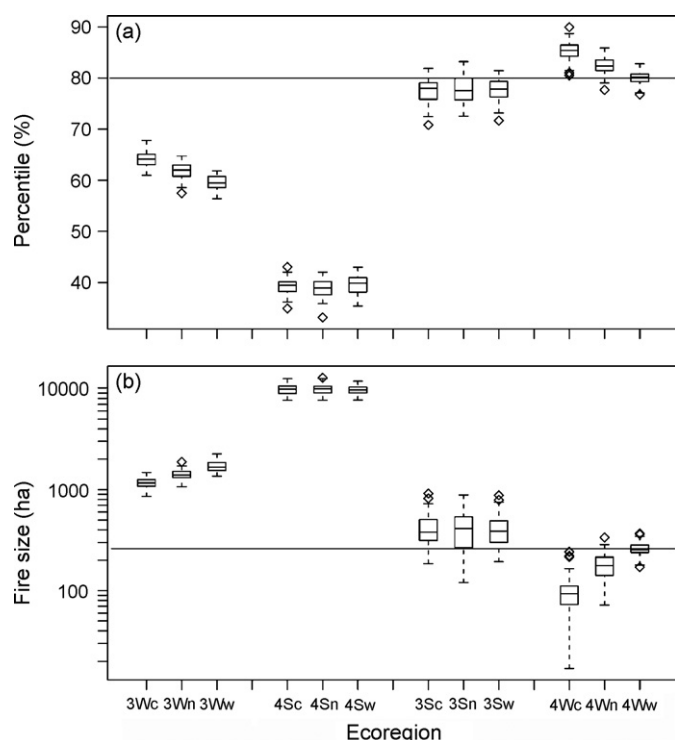


Fig. 5. A comparison of simulated fire sizes and forest policy directions for emulating natural disturbances in Ontario (OMNR, 2001) that limits 80% of the harvest patches to ≤ 260 ha in boreal forest: (a) the percentile at 260 ha fire size and (b) fire size at 80th percentile. Shaded lines show the policy direction limits (a) 80% and (b) 260 ha. Each eco-region (3W, 4S, 3S, and 4W)-fire weather scenario (c = cold, n = normal, w = warm) combination consists of 60 simulation runs of 200 years. Boxes indicate the interquartile range, middle lines the median, and whiskers the min-max values.

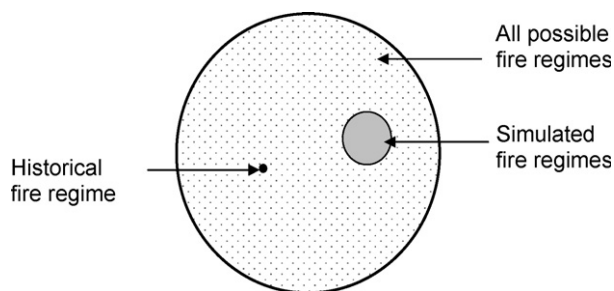


Fig. 6. A Venn diagram of relational domains of fire regime information for a given landscape. The larger circle represents all possible fire regimes that could occur; the smaller gray circle represents the simulated fire regimes of a given model, assumptions, and input data; and the point indicates the empirically reconstructed historical fire regime that did occur.

not known, it is impossible to assess whether the distance between fire history data and the simulation results is significant.

However, the overall message here is not the congruence of historical data with simulation results, but the fact that empirical data cannot provide the amplitude of information on spatial and temporal variability of fire sizes as well as the stochasticity that appears random (variability within known spatial biases and temporal correlations)—therefore remains a single point in Fig. 6. As pointed out by others (e.g., Lertzman et al., 1998, Suffling and Perera, 2004, Cary et al., 2006) even perfectly complete (spatially and temporally extensive) and accurate (without sampling biases and errors) empirical records of fire histories may provide a limited glimpse of spatial and temporal variability, and do not include stochasticity and certainly not responses of fire regimes due to contextual changes (e.g., Rupp et al., 2000).

At the same time, we do not at all imply that simulation results are 'real' or portray what would occur in nature with any certainty—therefore represents a small domain in Fig. 6. All simulation models are mere caricatures of nature, and can only portray the state of scientific knowledge and availability of data—they cannot compensate for shortcomings in either. Furthermore we stress that given the many uncertainties in scientific knowledge as well as data, simulated results of fire regimes must not be considered as forecasts of the future. Instead, they must be viewed as indications of the range of possibilities, strictly in the context of knowledge, assumptions, and data. Misunderstanding and misuse of landscape-scale simulation models is still common, mainly due to insufficient efforts in knowledge transfer (King and Perera, 2006). These limitations notwithstanding, simulation models, especially those with mechanistic logic, offer useful and defensible tools to guide forest management at long temporal scales and large spatial scales given their objectivity, transparency, and incremental improvability (Gustafson et al., in press). As knowledge and data improve, simulation models will be able to better portray the variability in fire regimes—become a larger circle in Fig. 6.

5. Conclusions

Natural fire regimes are variable and stochastic in nature, and all attempts to emulate those disturbances need to address that variability and stochasticity. Forest policies and management strategies must embody the variability of fire disturbance that is evident in space (e.g., due to forest cover, terrain, and climate) and time (e.g., due to changes in climate, vegetation patterns), as well as what may appear as random stochasticity (e.g., due to probabilistic nature of fire occurrence and behavior). They must do so at least at the scales that are feasible, given that it is impossible to understand (ecologically) and account (socially and economically) for variability at all spatial and temporal scales. The

breadth of variability associated with fire regimes cannot be readily captured from empirical data of fire histories, regardless of their popular and intuitive appeal. Even the most complete and accurate historical data is only one iteration of many possible eventualities of a highly complex and stochastic ecological process—and only answers the question *what did happen*. Simulation modeling provides a powerful means to understand all three sources of variability, as well as to explore potential scenarios of fire regime to inform forest management policies, and answer the question *what could happen*. In the short term, it will encounter difficulties such as discomfort with its abstract approach, large frames of spatio-temporal scale, and reliance on assumptions. However, in the long-term, simulation modeling is likely to be a valuable tool in developing spatially explicit strategies and policies that use variability of natural disturbances as a basis to achieve forest sustainability.

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