Modelling spatiotemporal variability of natural forest fire size class distribution in a boreal forest

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Abstract.

Forest fire size distribution describes the quantitative relationship between fire size and its corresponding number of occurrences in a forest landscape or region over a certain period. The knowledge of it has been used in forest fire management planning and assessment. However, there are still limitations in the empirical study of forest fire size distribution because the poor availability and low quality of fire data. In this study we explored the stochastic and spatio-temporal variability of forest fire size distribution of natural fires in a boreal forest landscape by way of simulation modelling and comparing it to empirical data. We found that fire size distribution is stochastic and has significant spatio-temporal variability which is decided by the causal factors that are stochastic and have spatial and temporal dimensions such as climate and weather, spatial composition of fuel types, topography, soil types, and water bodies. The burn probability near water body is much smaller that far from it by fires whose fires of larger size classes while burn probability by fires of smaller size classes seems more random in space. This findings has important implications for forest management planning such as deciding where to put harvest blocks.

Key words: simulation modelling, fire management, fire regime, burn probability

1. INTRODUCTION

Forest fire size distribution (FSD) can be defined as the probability of distribution of individual fire sizes that describes the quantitative relationship between fire size and its corresponding number of occurrences in a forest landscape or region over a certain period. Over the past decade, there are greater interest in using FSD as an indicator and/or parameter in the analysis of forest fire regimes. Overall, it seems that FSD is mostly likely to follow power-law or truncated power-law distriubtion, particularly in North American boreal forest based on the above research. The knowledge of FSD has also been used to formulate and evaluate forest policies and design long-term management strategies that guide harvest and forest management planning. For example, the province of Ontario, Canada made forest policies in a forest management guide that specifies directions to plan forest harvest patterns based on derived from empirical observations of recent fire history (OMNR 2001). Knowledge of FSD is also important for fire management planning and assessment. For detailed information about FSD see the review by Cui and Perera (2008).

In spite of the importance and widely use of FSD knowledge in research and applications, there are still limitations. First is that the knowledge of FSD itself is not complete and reliable; most empirical knowledge are sometimes based on the poor quality or insufficient data. Second, the empirical data usually come from relatively small temporal and spatial scales of observations. Short observation periods mean fewer fires, which may not be sufficient to derive reliable FSDs. Most importantly, it is very difficult to extract the spatio-temporal trend of FSD which are very important in formulating and assessing forest management plans and policies. Besides, forest fire regimes not only vary over time and space but also are highly stochastic, which means that if given many chances the fire history will be different each time in a forest landscape over a time period. So it is also true that FSD in a forest landscape has the three aspects of forest fire regime. There is little research in these aspects so far.

Our goal in this study is to investigate the stochastic and spatio-temporal variability of FSD of natural fires in a boreal forest landscape by way of spatio-temporally explicitly modelling the forest fire regimes over a large region over various length of time. Natural fires are defined as forest fires that are lighting-caused and unsuppressed. We also study the empirical FSD through historical records of forest fires in the region and comparing it the simulated FSD.

As there are still aspects of forest fire sciences not fully explored, we make explicit assumptions in those aspects. One thing we want to emphasize is that we do not try to predict FSD but to explore the stochastic and spatio-temporal variability of it given what we know.

2. METHODS

2.1. Study area

To fully study spatial aspect of forest fire regime and FSD in particular, we selected a large boreal forest regeion in the province of Ontario, Canada, as shown in Fig. 1. The study area was classified as ecoregion 3W with five eco-districts based on geo-climatic patterns (Fig. 1). The study area is 8.8 million ha, of which 7.4 million ha is forested. The sizes of the five eco-districts are 2.59, 2.36, 1.70, 1.49, and .73 million ha for eco-districts 1, 2, 3, 4, and 5 respectively. The smallest eco-district is almost as large Yellow Stone National Park of USA. The study area is of cold-dry climate type and has well drained soil. The rolling terrains of the area are interspersed with lakes and the dominant forest cover types are conifer and mixed-conifer forest.

There are many natural disturbances such as insects, forest diseases, and wind throws occurring in the study area. However, the primary natural disturbance regime is periodic stand-replacing fires and there are also forest harvest activities. Most of the study area is in Ontario's boreal fire management zone where aggressive suppression of wildfires has been part of the Ontario's fire management strategy for up to 80 years.

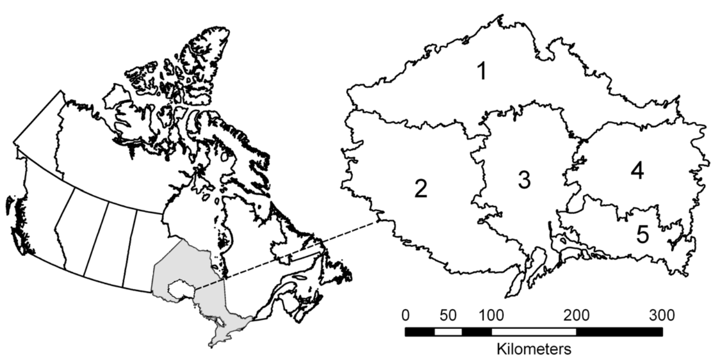

Figure 1. The case study area is the entire ecoregion 3W in the province of Ontario, Canada. The ecoregion include five eco-districts.

2.2. Simulation model

We used BFOLDS to model the fire regime and thus to study FSD in the study area. Details of BFOLDS model are described by Perera *et al*. (2008) (http://www.flep.ca/publications/bfolds.html). We just describe the major features, assumptions, and input relevant to this study in the paper. BFOLDS is strategic forest fire regime model that simulates forest fire processes and forest succession spatially explicitly in a large forest landscape over a long period. Its fire module is mostly process-based and succession module empirical. BFOLDS is also stochastic, resulting from its stochastic simulation of fire ignition, fire extinguishment, and forest succession. BFOLDS mechanistically simulate processes of fire ignition, fire spread, and fire extinguishment as a function of fire weather, topography, and fuel patterns based on the Canadian Fire Behaviour Prediction system and Canadian Forest Fire Weather Index System. BFOLDS is raster-based and simulates multiple fire events on a given landscape at 1 ha resolution and in continuous time. The characteristics of BFOLDS can better simulate the three-dimensional characteristics (stochastic, spatio-temporally variable) of forest fire regime.

BFOLDS can use historical weather data as well as any data sources such as those from climate change models as long as they use the same contents and formats. In this study, we assumed that the future weather is similar to those recorded during the 42-year history of weather records (1963-2004), in order to account for the uncertainty of knowledge of fire weather including the daily number of lightning-caused fire ignitions. For each simulation year, a historical weather year was randomly selected. However, the selection of days was the natural sequence of the selected weather year.

In BOLFDS, long-term forest succession was stochastically simulated at 1 ha resolution, based on a time-dependent Markov chain. The simulated forest cover change with time was either due to ageing and/or due to fire disturbances and subsequent succession.

2.3. Simulation study design

To study the temporal variability of fire regime and FSD in particular, we used six simulation periods: 20, 50, 100, 200, 1000, and 2000 years. Thirty simulations were run for each period to capture the variability in the fire regime. We used the present-day forest cover (such as cover type and age) as the year-zero state to seed subsequent forest dynamics. To allow fires that could originate outside to spread into the study area, we imposed a 20-km-wide external buffer. Spatial data used in the simulation study include forest cover type, age, soil moisture and nutrient, slope and aspect, and fire ignition pattern.

3. Results

3.1. Number of fires and area burned

In order to compare numbers of fires and area burned among eco-districts and various simulation periods, we used average annual number of fires (ANF) over the study period per million ha for number of fires and average annual burn fraction (ABF) over the study period for annual burn fraction.

$$ANF = \frac{Total\ number\ of\ fires\ in\ the\ period}{Number\ of\ years\ in\ the\ period} \times \frac{1000{,}000}{Total\ forested\ area} \qquad (1)$$

$$ABF = \frac{Total\ area\ burned\ over\ the\ simulation\ period}{Number\ of\ years \times Total\ forested\ area} \qquad (2)$$

Figure 2 shows the ANFs of the study area and its five eco-districts over a 200-year period. It can be seen that (1)ANFs differ among eco-districts but also between the whole study area and the eco-districts and (2) ANFs have large variations for the study area and each of its five eco-districts.

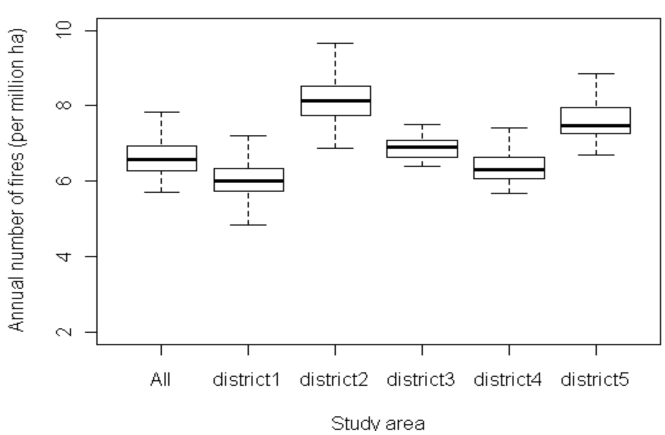

Figure 2. Average annual number of fires per million ha in the study area and its five eco-districts for a 200-year period (n = 30 simulations). Box indicates the interquartile range, middle line the median, and whiskers the min-max values.

Similarly, figure 3 shows that the ABFs of the study area and its five eco-districts over a 200-year period. It can be seen that (1) ABFs differ among eco-districts but also between the whole study area and the eco-districts and (2) ABFs have large variations for the study area and each of its five eco-districts.

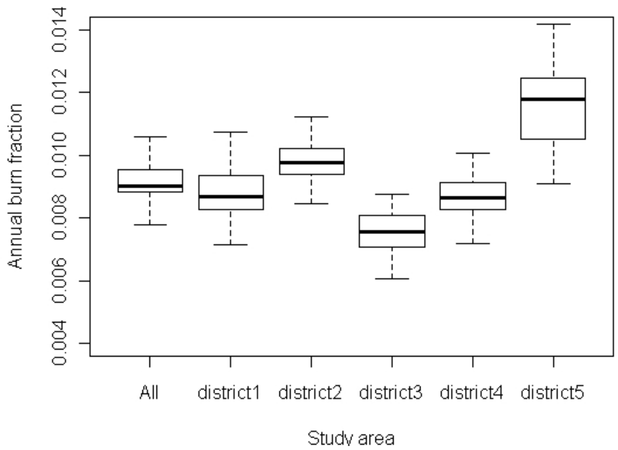

Figure 3. Average annual burn fraction (ABF) in the study area and its five eco-districts for the 200-year period (n = 30 simulations). Box indicates the interquartile range, middle line the median, and whiskers the min-max values.

The spatial variability can also be seen by the annual burn fraction map. *ABF* at cell *i* is defined as:

$$ABF_i = \frac{Number\ of\ times\ cell\ i\ burned}{Number\ of\ simulation\ years} \qquad (3)$$

From the mathematical definition of spatial *ABF*, we know ABF_i can be seen the same as spatial annual burn probability (ABP_i). Figure 4 show a map of average *ABF* or *ABP* of 30 simulations over the 200-year period. It spatially explicitly shows how *ABF* varies across the study area and within each eco-district.

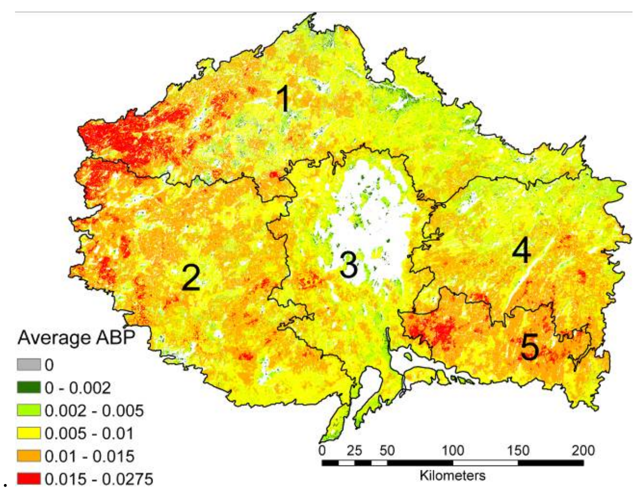

Figure 4. The map of average annual burn fraction of 30 simulations over the 200-year period in the study area.

3.2. Fire size class distribution

The focus of this study is what FSD in the study area and its stochastic and spatio-temporal variability is, but not what mathematical equations better describe the FSD. Thus based on the knowledge that the FSD mostly likely to follow power-law or truncated power-law distribution, we divided fire sizes into four classes: (0,100], (100, 1000], (1000, 10000], and (10000, ∞] ha which we call class1, class2, class3, and class4 respectively.

We also extracted empirical FSD using the forest fire database of the Ontario Ministry of Natural Resources of 49 years (from 1960 to 2008). The empirical fire data set may be viewed as an alternate replicate to simulated fire data. To compare the FSD difference between study area and its eco-districts and among the eco-districts, we used the number of fires per 100 year per million ha for number of fires.

Figure 5 shows the simulated FSDs of the study area and its five eco-districts over the 200-year periods of 30 simulations and the empirical FSD based on 49 years (1960-2008) fire records. From it we can see that (1) overall there are more small fires than large fires, (2) simulated FSDs has significant stochastic variations, (3) there are FSD differences between study area and its eco-districts and among the eco-districts, and (4) there are differences between empirical FSDs and simulated FSDs which is that the latter has much fewer smaller fires and more large fires than the former.

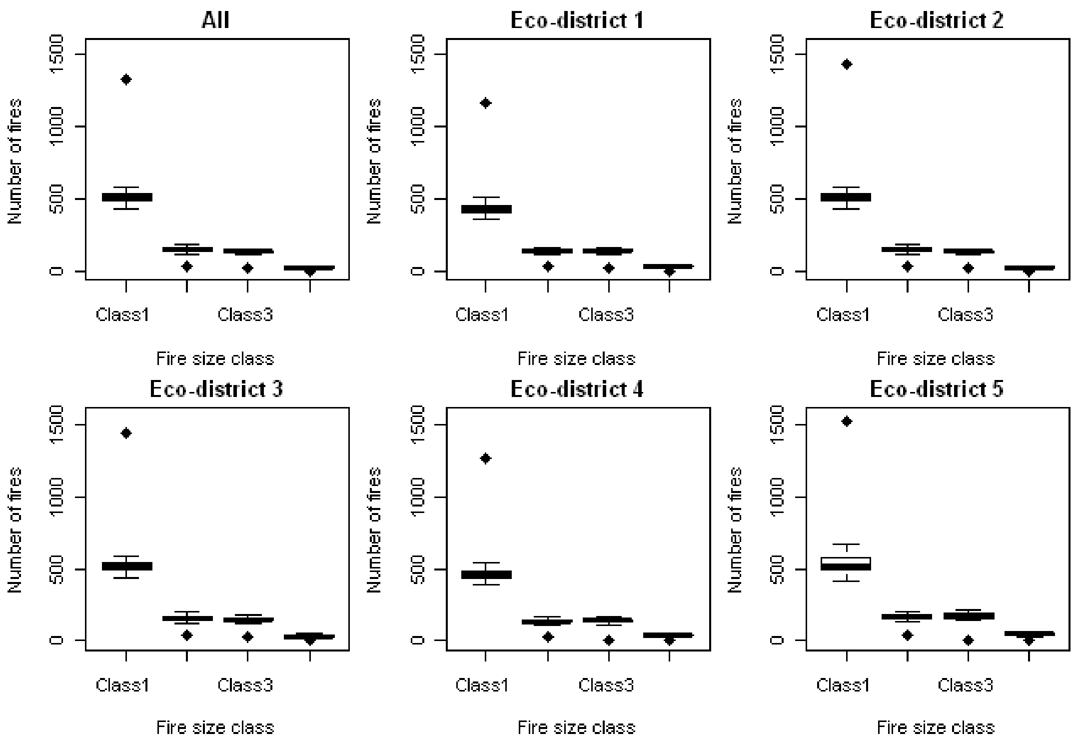

Figure 5. Cumulative fire size class distributions of forest fires in the study area for the 200-year period (n = 30 simulations). Box indicates the interquartile range, middle line the median, and whiskers the min-max values. The four classes - class1, class2, class3, and class4 are (0,100], (100, 1000], (1000, 10000], and (10000, ∞] ha respectively. The dark symbols (♦) represent empirical data. Note: the numbers of fires here were normalized to the numbers of fires per million ha per 100 years.

Figure 6 shows the simulated FSDs of the study area over the periods of 20, 50, 100, 200, and 1000, and 2000 years of 30 simulations and empirical FSDs over the periods of 20 years (1960-1979) and 49 years (1960-2008). To compare the empirical FSD of 49 years to simulated FSD of 50 years, we multiplied the empirical number of fires of each size class by 50/49. Similarly, to compare the FSD difference among the study periods, we used the number of fires per 100 year per million ha for number of fires.

We can see that (1) simulated FSD has significant stochastic variations but there are more variations in shorter periods than in longer periods, (2) there are FSD differences among various lengths of periods but FSDs are more similar for the longer periods such as those of 1000 years and 2000 years as shown in Figure 6, and (3) difference of empirical FSD between periods of 20 years and 49 (or standardized 50) years is even bigger.

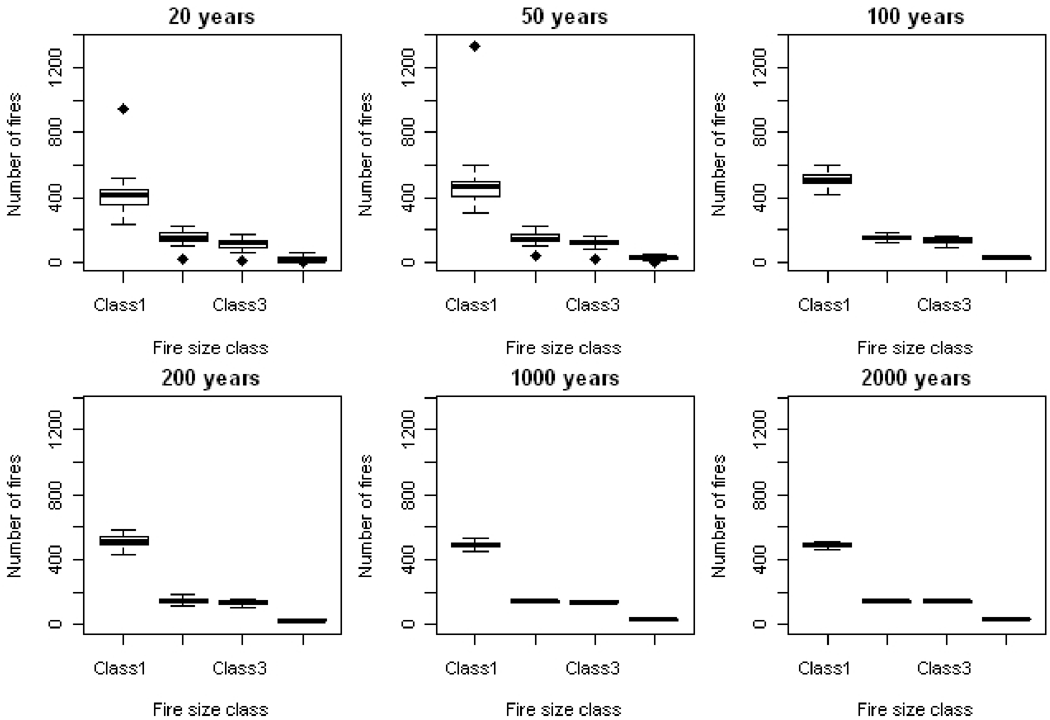

Figure 6. Cumulative fire size class distributions of forest fires in the study area for periods of 20, 50, 100, 200, 1000, and 2000 simulation years (n = 30 simulations). Box indicates the interquartile range, middle line the median, and whiskers the min-max values. The four classes - class1, class2, class3, and class4 are (0,100], (100, 1000], (1000, 10000], and (10000, ∞] ha respectively. The dark symbols (♦) represent empirical data (see text for details). Note: the numbers of fires here were normalized to the numbers of fires per million ha per 100 years.

Despite the large number of smaller fires, they only account for much smaller area burned over the study area over the 200-year period. Percents of area burned are 0.5, 6.6, 45.3, and 47.6 for fire size class (0,100], (100, 1000], (1000, 10000], and (10000, ∞] ha respectively. This fact make it necessary to if a place is burned, what is the probability of it being burned by a particular fire size class.

3.3. Burn probability by size class

We defined burn probability by size class as:

$$ABP_{ci} = \frac{Number\ of\ times\ cell\ i\ is\ burned\ by\ fires\ of\ size\ class\ c}{Number\ of\ simulation\ years} \quad (4)$$

where c is the fire size class, ABP_{ci} is the annual burn probability of cell i by forest fires whose sizes belong to size class c over the simulation period in the study area.

Figure 7 shows *ABPs* of size classes of (0,100], (100, 1000], (1000, 10000], and (10000, ∞] ha respectively. From the figure we can see that (1) the burn probability by fires of smaller size classes are relatively small and more evenly or randomly distributed spatially; (2) the burn probability by fires of larger size classes is relatively large overall but they are greatly influenced by fire barriers such as lakes – ABPs in areas near fire barriers much smaller than those in areas far the barriers and it is more true for even larger fire size classes. For small islands, they are more likely to be burned by fires of smaller fire size classes and no chance to be burned by fires whose size are larger the island.

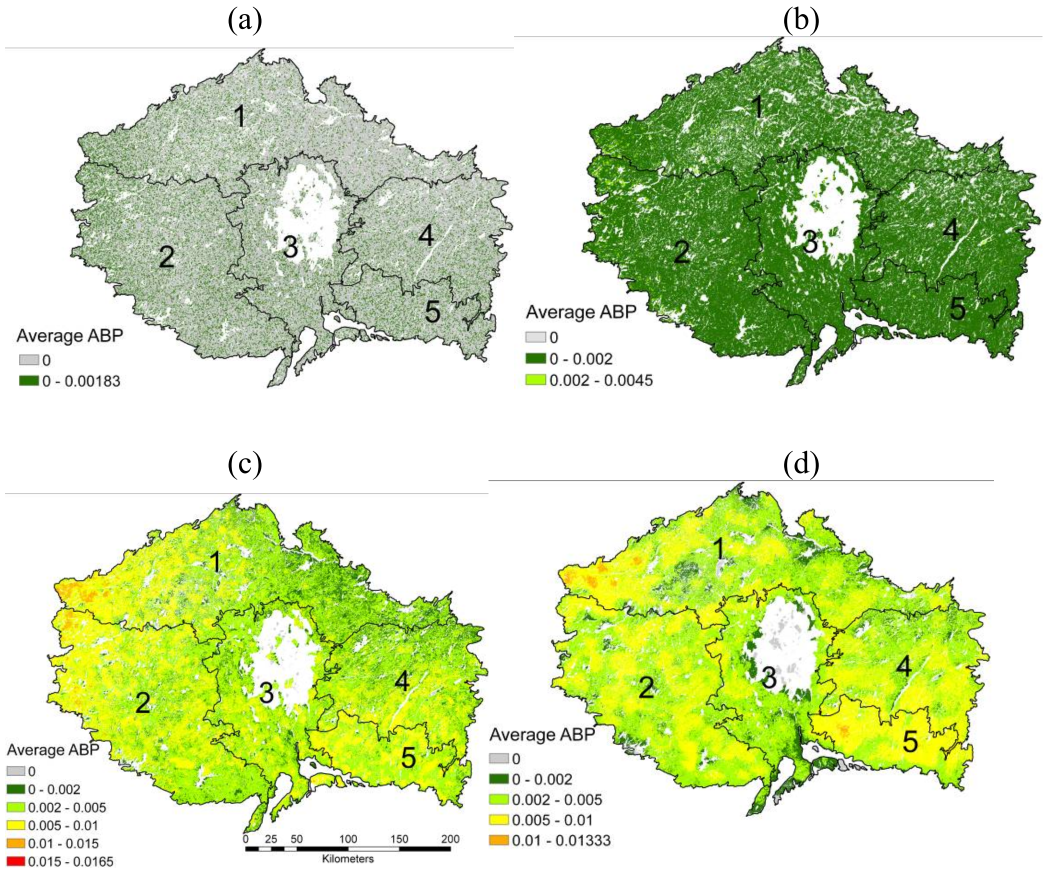

Figure 7. Average *ABP* by fires of size classes of (a) (0,100], (b) (100, 1000], (c) (1000, 10000], and (d) (10000, ∞] ha respectively.

4. DISCUSSION

4.1. Stochasticity of FSD

FSD as an indicator of forest fire regimes is stochastic as shown in the results section. This is indicated by (1) overall FSD in the study area and FSDs of the eoc-districts, (2) overall FSDs of various lengths of simulation periods. Fundamentally, the stochasticity of FSD comes from stochastic characteristics of natural forest fire regimes. There are many factors that decide and influence the ignition, spread, and extinguishment of forest fires. Some of these factors are highly stochastic overall, over time, and over space. For example, climate and weather and the resulting lightening strikes are highly variable in timing, duration, strength, space, and extant. Number of lightning fires and the timing and location of each fire are not determined but subject to chances though they have some patterns overall. The spread and extinguishment process of each fire after successful ignition is also greatly influenced by the local conditions, which include many factors such as fuel types, topography, soil types, and natural fire barriers. This explains, at least partly, why the number of fires and the timing, location, and each fire varies a lot, thus FSD varies randomly. The stochasticity means that for a forest landscape it will have as many number of trajectories of fire histories as the number of chances it is given if possible.

Stochasticity of FSD means people have to realize the empirical FSD extracted from historical fire history is just one of many possibilities and variations of FSD may have to be taken account in applications.

4.2. Spatio-temporal variability of FSD

Despite the stochasticity or randomness of FSD, FSD also has trends or patterns over time and space. FSD not only differs by location such as each eco-district has different overall FSDs but also that chances at any location being burned by fires of a particular size classes are different.

The underlying reasons for the spatial variability of FSD are that the many factors that make forest fire regimes random also make temporally and spatially different. Climate and weather and the resulting lightning strikes have spatial patterns that can make fires ignites more easily in one place than other. The spatial fuel type and forest age composition, topography, and soil type make fires spread more quickly and extinguish more difficult in some area than other. Besides forest landscape structure also affect fire size thus affect FSD spatially. Burn probability of being fires of smaller size classes distributed evenly over space and might be a little influenced by the historical igntion pattern. However, burn probability being burned by fires of larger size classes are greatly influenced by fire barriers – areas near water bodies have much lower probability than areas far away from the water bodies. In small islands, they can only be burned by fires of smaller size class and cannot be burned by fires larger than its size at all.

The spatail variability of FSD has important implications for forest management where policies of emulating natural fire disturbances are implemented. For example, because of smaller probability of being burned by fires of larger size classes near water bodies, large forest harvest blocks must be away from water bodies and smaller harvest blocks can have less constraints in this respect.

In this study, we only found there are signifant temporal variability. However, we did extract the temporal trend of FSD. One reason is that we randomly selected historical years over the simulation periods and the patterns of trends, if there, any were covered up.

4.3. Empirical study of FSD

In this study the simulated FSD is significant different from empirical ones. There are several possibilities for this. The simulated FSD is of "natural" forest fires that are lightning-caused but not suppressed while the empirical FSD is of forest fires that most of them have been aggressively suppressed. Fire suppression generally result in many smaller fires and fewer medium and large fires because successful initial attack in Ontario, Canada stops fire from spreading when they small and limit fire sizes even fires are out of control. This may be one of the most important reasons that simulated FSDs are different from empirical ones.

One other possibility is that there are some knowledge gaps in fire science and we used some assumptions in BFOLDS. For example, we assumed that fire extinguishment was solely decided by DMC.

From this study we can see empirical FSD give us some idea of what happened in the past in the study area over a 49-year period. However, empirical study cannot provide the range of variations caused by stochasticity of forest fire regime, it cannot provide spatially explicit FSD, and can only be used to temporal trends of FSD very coarsely. Besides, empirical study is limited by the availability and quality of data both in the size of study area and duration of record. Empircal data also is difficult in studying causal factors of FSD. In this study, for example, we can not get data of lightning-caused and usuppressed fires

Simulation modelling, on the other hand, is free from these limitations. Some models can be used to address various what-if and/or if-then questions asked by forest researchers and land managers. And certainly, models like BOFLDS that simulate forest fires mechanically and spatio-temporally explicitly, can better be used to explore the three dimensions of FSDs – stochasticity, spatial and temporal variability.

5. References

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