1995 BOYC

Animating Forest Fire Regimes and Dynamic Landscape Age Structure

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Abstract

It is important to identify the natural state of forest landscapes, but that is difficult after many decades of fire protection and harvesting. Our objective was to provide insight into some factors that determine landscape age structure or distribution (LAD) in a fire-dominated forest ecosystem. In particular, we examined Van Wagner's exponential model of boreal forest LAD and its temporal stability. For this theoretical analysis, we developed a PC-based dynamic spatial simulation model of a fire-disturbed landscape. We used a simple homogeneous forest and different disturbance regimes to identify the fundamental determinants of LAD. The model animates the forest changing due to fires and growth, and simultaneously graphs the LAD. The model allows us to test the effect of forest size, disturbance rate, fire size distribution, and temporal disturbance pattern. It demonstrates the effect of spatially and temporally correlated fire disturbances due to "weather." Our results show that LAD can be unstable even at very large scales due to the correlation of disturbances.

1995 In Proc 9 Int. Geomatics Conf.
CD-ROM
National Defense
Geomatics Canada
Ottawa. ON

1. Introduction

An important concern in forest management is the extent to which the current and future states of the forest resemble its "natural" state in the distant past. It is well known that fire and other disturbances have played important roles in shaping Ontario's forest ecosystems under natural conditions (e.g., Heinselman 1973). It is often difficult or impossible, however, to reconstruct the history of the forest and characterise its natural state. This is primarily due to the cumulative impact of factors like fire protection and harvesting during this century. Even where it is possible to reconstruct the past forest state, it is expensive and limited data are available. Indeed, the fire history of a given forest might be considered as only one sample point as it is one realisation of a stochastic process.

To complement the limited empirical data, it is useful to use theoretical models to gain insight into the dynamics of this complex system (e.g., Baker 1989a, 1989c, 1992, 1993; Mladenoff 1994). Van Wagner (1978) gave us valuable insight into the natural dynamics of forest age structure or distribution with the exponential model. Van Wagner developed a simulation model of a forest composed of equal-sized, homogeneous, independent cells or stands which were subject to the risk of burning each year. Regarding his model, he wrote that

> " ... there is no fundamental reason why ... individual fires could not burn more than one stand. ... Similarly, there is no reason why the burned area could not vary from year to year ... Such departures from the ideal would naturally result in statistical roughness but need not disqualify the negative exponential concept."

Our objective was to examine these and other factors more closely, and identify the theoretical conditions under which the exponential model might and might not closely describe landscape age distribution. We also examined whether the landscape age distribution is stable or variable over time. Specifically, we considered the following factors:

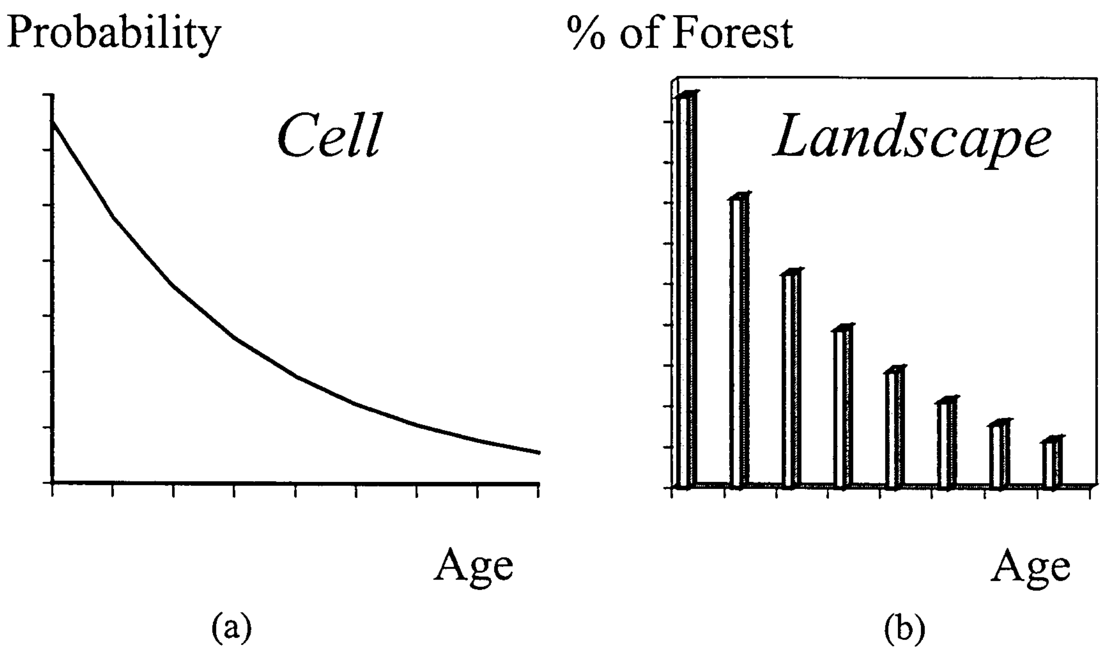
- forest size
- disturbance rate
- whether each fire burns only one cell, or can grow to adjacent cells
- whether all years have the same average disturbance rate, or some years are more severe than others.

For our work, we developed a spatial simulation model called FLAP-X (**F**ire and **LA**ndscape **P**atterns – e**X**ponential age distribution). FLAP-X was not designed to be a comprehensive model of forest dynamics. It is a relatively simple model that focuses on the consequences of alternative spatial and temporal characteristics of fire disturbance. To isolate the basic factors that determine the landscape age distribution, we used a simple homogeneous forest. FLAP-X models the forest as a collection of cells. The cells are distinguished by their age, which is the time since the last fire. During each simulated year, each cell either burns or ages. FLAP-X displays the forest changing over time due to ageing and renewal by fire, and simultaneously graphs the landscape age distribution. FLAP-X provides both a graphical view of the dynamics and numerical output for analysis.

2. Theoretical Basis of the Exponential Model

2.1. Single Cell Level

The exponential age distribution model originates from the single stand or cell level. From the properties of the exponential distribution (e.g., Ross 1972), if the probability of burning a cell is constant and independent of stand age, then (1) the probability distribution of the time between fires is exponential, and (2) the probability distribution of the age of the cell is exponential. This is illustrated in Figure 1 (a). In the long term when the influence of the initial conditions has disappeared, the probability distribution of the age of the cell is exponential.



(a)

(b)

Figure 1: Illustrations of (a) the exponential probability density function of cell age, and (b) the exponential shape of the corresponding landscape age distribution.

2.2. Landscape Level

The exponential model is extended from the single stand to the landscape level as follows (Harrington and Donnelly 1978, Van Wagner 1978, Reed 1980, Wilson 1983). We assume that the forest consists of a collection of equal, independent single stands or cells of unspecified size. Stands are assumed to either burn entirely or not at all during a particular year. They burn independently of each other, and with the same probability regardless of age. Because the forest consists of "many" cells, the landscape age distribution is simply a large sample from the exponential distribution. With a sufficient number of cells, the landscape age distribution will also have the exponential shape. This is illustrated in Figure 1 (b).

3. Overview of FLAP-X

FLAP-X is based on the cell models by Van Wagner (1978, 1983, 1986), Wilson (1983), and Antonovski et al. (1992). We can specify a wide range of values for several parameters, namely the:

- number of cells in the forest
- expected fire size
- variability of fire size (constant or geometrically distributed)
- expected annual proportion of the forest burned, and
- variability of expected annual proportion of the forest burned over time.

We are particularly interested in evaluating the effect of two kinds of dependencies of burning among cells that are not represented in the classical exponential model described in Section 2:

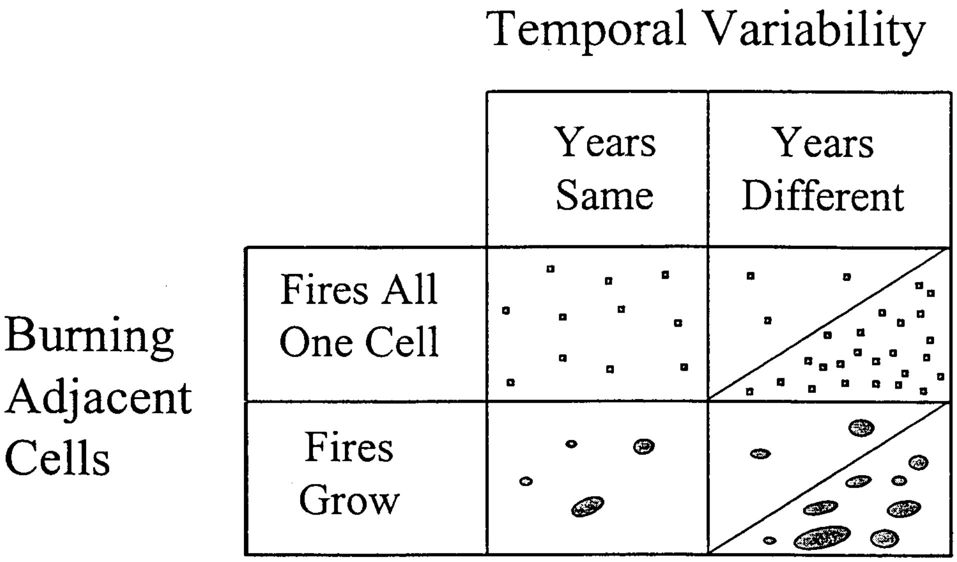
- burning adjacent cells due to fire growth, and
- correlation of high and low disturbances over large areas due to weather.

We organised the many possible alternatives into four spatial and temporal disturbance patterns which are listed in Table 1 and illustrated in Figure 2. Note that we can specify the expected annual proportion burned for all four disturbance patterns in advance, in order to compare the effect of the disturbance pattern on an equal basis.

Table 1: The four spatial and temporal disturbance patterns in FLAP-X

		Temporal Variability	
		Years Same	**Years Different**
Burning Adjacent Cells	**Fires All One Cell**	Disturbance Pattern 1: YS-F1	Disturbance Pattern 3: YD-F1
	Fires Grow	Disturbance Pattern 2: YS-FG	Disturbance Pattern 4: YD-FG

Figure 2: Illustration of fires for the four spatial and temporal disturbance patterns used.



Disturbance Pattern 1: Years Same – Fires One Cell: Fires burn only one cell each. Each year has the same expected proportion burned.

Disturbance Pattern 2: Years Same – Fires Grow: Fires grow to adjacent cells. Each year has the same expected proportion burned.

Disturbance Pattern 3: Years Different – Fires One Cell: Fires burn only one cell each. Some years have a higher expected proportion burned than other years. In the years with the higher expected proportion burned, all cells have a higher probability of burning due to a larger expected number of fires in the forest.

Disturbance Pattern 4: Years Different – Fires Grow: Fires grow to adjacent cells. Some years have a higher expected proportion burned than other years.

4. Computational Results

It is instructive to run FLAP-X with a variety of settings to see the spatial pattern in the forest and the age distribution graphs changing over time. Here, we present the principal results. Note that in all of the results presented here, the age class width is one year. Figure 3 shows the effect of the expected proportion burned in a forest. In both cases, the forest size is 160 000 cells, all years are the same, and all fires are fixed at one cell (Disturbance Pattern 1). In one case the expected percentage burned is 2.5% and in the other case it is 1.5%. The age distribution graphs are not smooth due to randomness, but they both closely match the theoretical exponential distributions with their corresponding means.

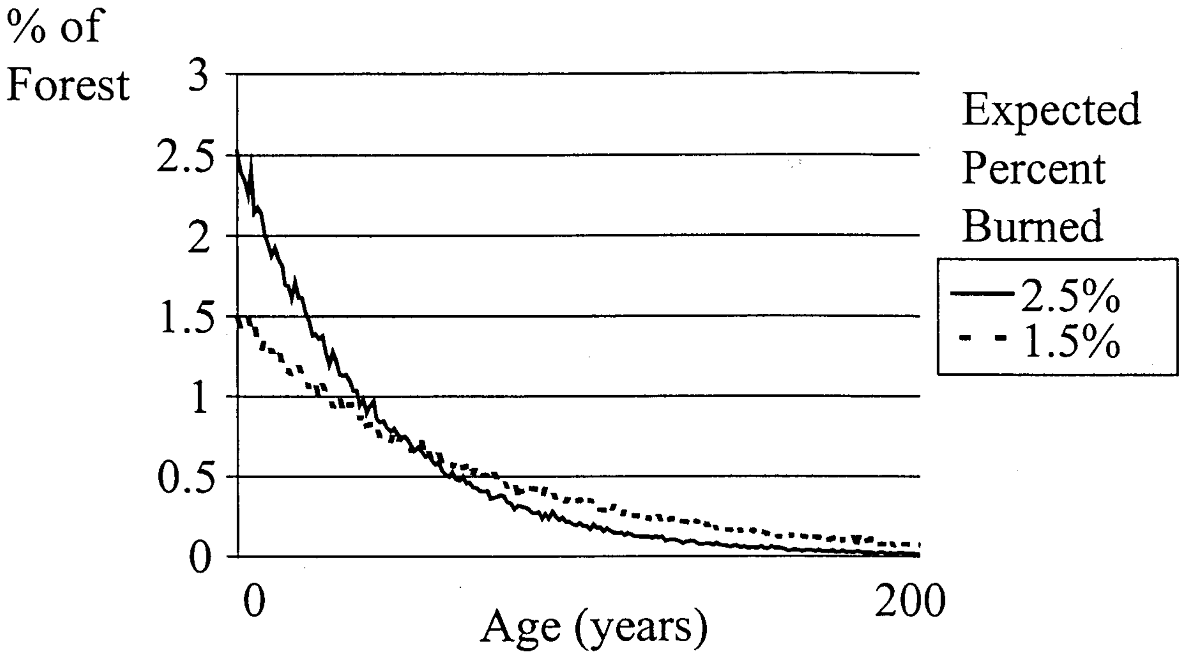


Figure 3: Sample age distributions showing the effect of the expected annual percentage burned. A higher value leads to more area in the younger ages and less area in the older ages.

Figure 4 shows the effect of the number of cells in the forest. In all cases Disturbance Pattern 1 is used (YS-F1) with an expected proportion burned of 1.5%. The results show sample age distributions at a single point in time, and are given for forest sizes of 400, 10 000, and 160 000 cells, along with the corresponding smooth theoretical curve. For forests with fewer cells, the age distribution varies widely around the exponential shape due to the small sample size.

Figure 5 shows the effect of the four disturbance patterns. In all cases, the forest size is 90 000 cells and the overall expected proportion burned is 1.5%. The results show sample age distributions and the corresponding theoretical exponential age distribution. For the disturbance patterns in which fires grow (FG), the expected fire size is 15 cells. Where years are different (YD), the expected proportion burned in the 3 of 10 worst years is 4%. Even for this relatively large forest, where years are different (YD), the age distribution is highly variable. Significantly, the age distribution *averaged over time* is exactly exponential for all for disturbance patterns.

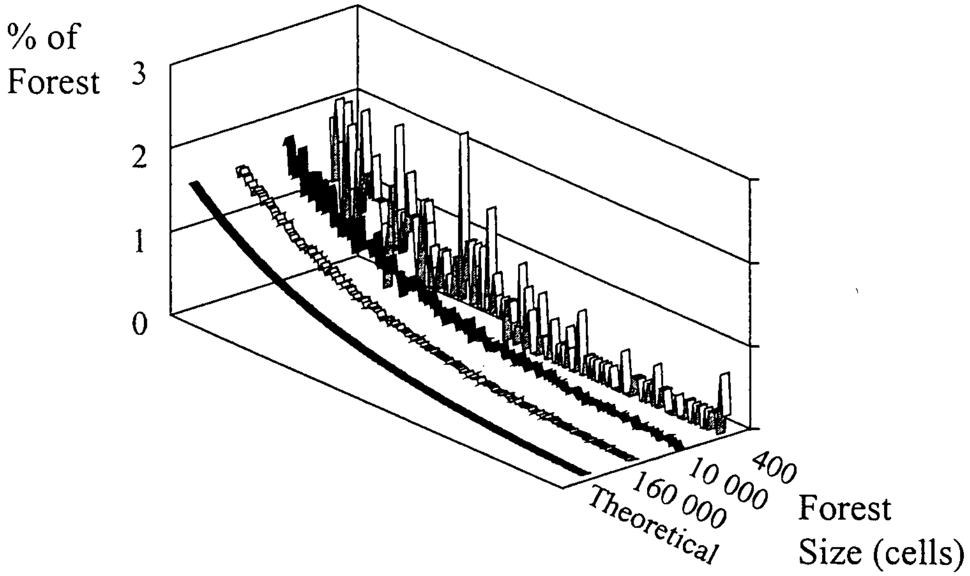


Figure 4: Sample age distributions showing the effect of the forest size.

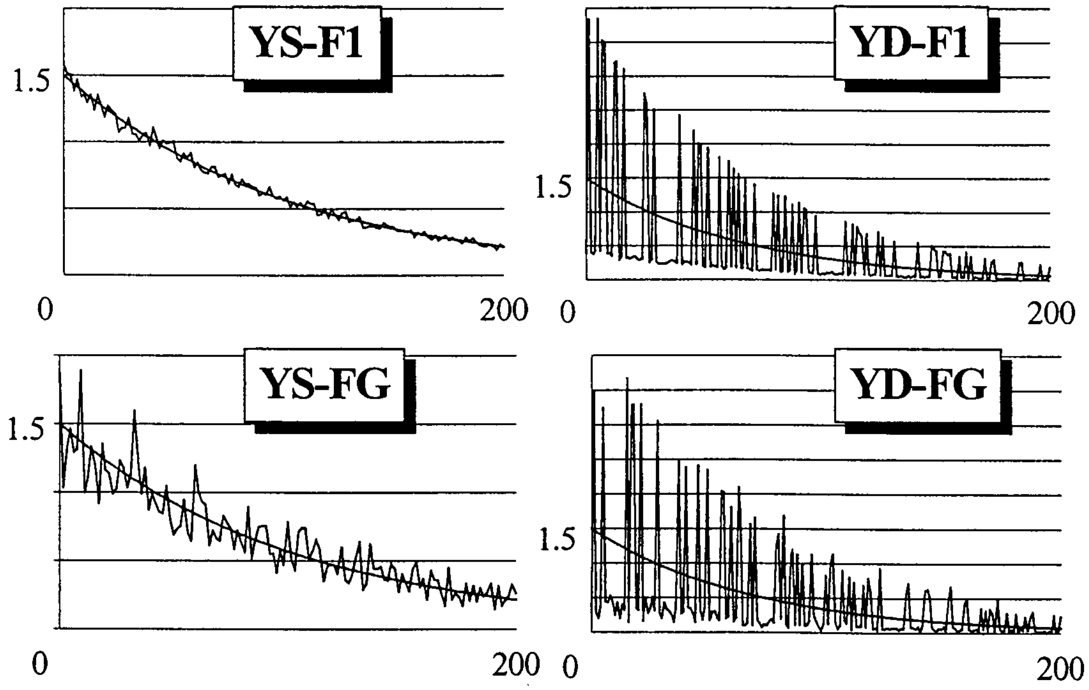


Figure 5: Four sample age distributions showing the effect of the disturbance pattern.

One of the principal questions in our analysis is whether the landscape age distribution approaches the exponential shape for "sufficiently large" forests. For this we used "SIM," a similarity index used by Baker (1989c) to measure the degree to which any given age distribution matches the corresponding theoretical age distribution. SIM can range from 0% to 100%. The sample age distributions in Figure 5 have the following approximate SIM values:

YS-F1, SIM = 98%	**YD-F1, SIM = 50%**
YS-FG, SIM = 92%	**YD-FG, SIM = 50%**

Figure 6 shows average SIM vs. forest size for the four disturbance patterns. For Disturbance Patterns 1 and 2 (YS-F1, YS-FG), SIM approaches 100% for sufficiently large forests. For Disturbance Pattern 2 (YS-FG), however, the forest needs to be roughly 15 times larger than for Disturbance Pattern 1 (YS-F1) to get the same SIM, because its average fire size is 15 cells. Where years are different (YD), SIM never approaches 100% because the disturbances are correlated throughout the forest, and the age distribution always varies around the theoretical or average distribution.

Note that the specific results depended on the expected proportion burned, the expected fire size, how much years differ, and the age class width. The relative positions of the curves in Figure 6 can change significantly for different scenarios.

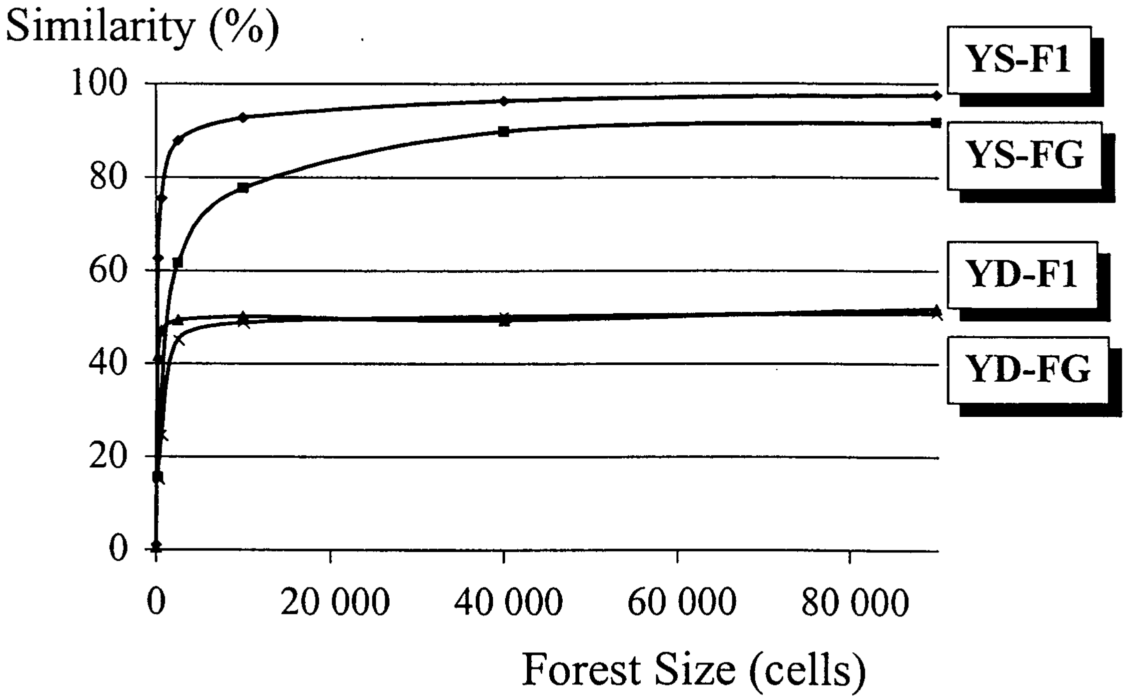


Figure 6: Average similarity index vs. forest size for the four disturbance patterns.

Finally, we present an alternative illustration of the variability of the landscape age distribution by showing seven independent sample age distributions along with the theoretical age distribution (Figure 7). We used a forest of 40 000 cells in size, an expected fire size of 24 cells, an overall expected proportion burned of 1.4%, and an expected proportion burned in the worst three out of 10 years of 4.5% (i.e., Disturbance Pattern 4: YD-FG). Note that the age class age class width is 20 years and the distribution extends further, but the higher age classes are absent from the graph. If we used the assumptions in the classical exponential model, with all years being the same and fire sizes of one cell (i.e., Disturbance Pattern 1: YS-F1), then the sample age distributions would all be very close to the theoretical age distribution.

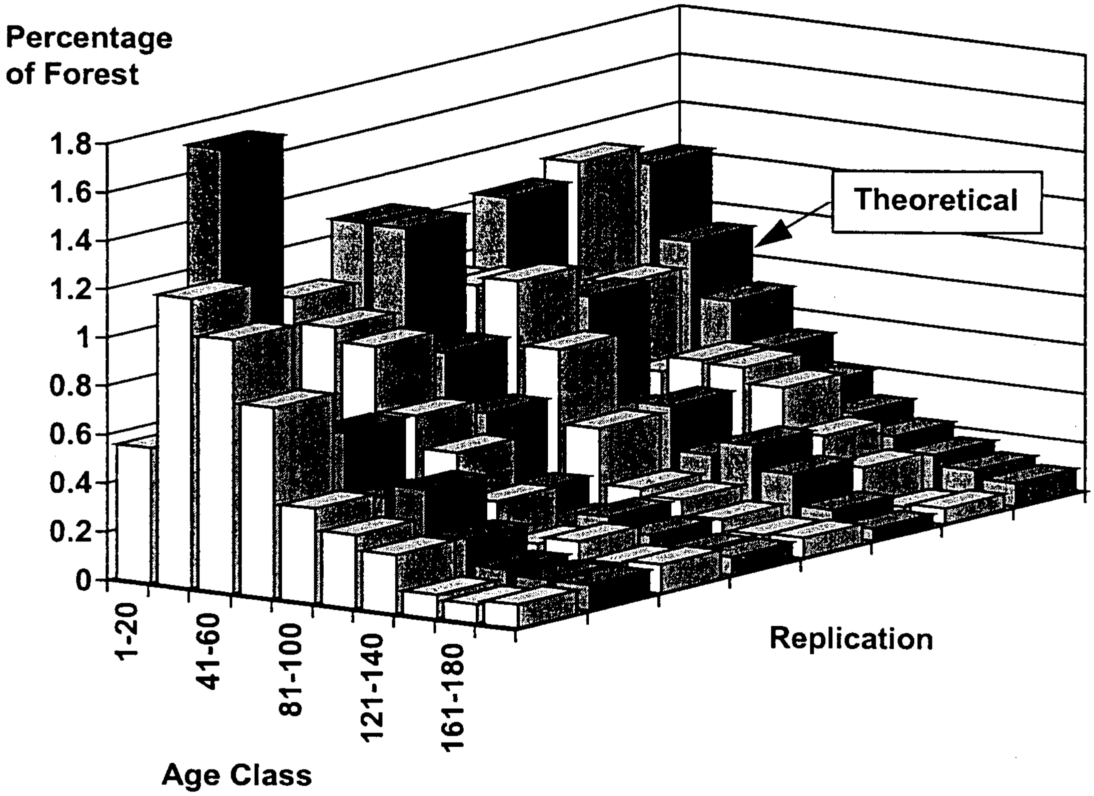


Figure 7: Illustration of the variability of the age distribution. Seven independent sample age class distributions are shown along with the theoretical age class distribution. Note that the age distribution continues into older classes which are not shown.

5. Discussion

Our purpose was to gain insight into the dynamics of a system subject to random disturbances. We believe that this research gives useful insights for our understanding the dynamics of landscapes that are subject to fire disturbances. Our results suggest that, under plausible natural boreal disturbance regimes, we should not expect to find landscape stability even at very large scales due to spatial and temporal dependence of disturbances. We note, however, that the exponential model represented the *average age distribution over time* for all disturbance patterns.

We emphasise that this model and its results and conclusions are theoretical. We have analysed the consequences of the assumptions in our model. We can make no claims about the dynamics of actual landscape age distributions from this work alone. We are, however, developing refined models and will test them with empirical data. A significant amount of work has been done previously on the analysis of empirical age distribution data (e.g., Van Wagner 1978, Suffling et al. 1982, Suffling 1983, Baker 1989b), much of which used Van Wagner's exponential model in some way. Baker (1989c) analysed the fire regime in the Boundary Waters Canoe Area with a Markov chain model, and found that the forest age class distribution did not form a stable exponential shape there. The insights gained from our theoretical work might aid in the further analysis of empirical data. In addition, we have demonstrated that it is important to represent the spatial and temporal correlations of disturbances in landscape simulation models.

Based on the empirical and theoretical work, it appears to be necessary to allow for variability – sometimes significant variability – when attempting to identify the natural state of the landscape. In the presence of variable disturbances and spatial and temporal dependence, applying the exponential age distribution model to forest management could lead to problems. For example, if the forest was managed to maintain an exponential age distribution at small, local scales, there would be an absence of large disturbances. If the variability of disturbance sizes was recognised, but the effect of scale was not considered, another type of problem could result. For example, decision-makers at every local forest unit could, in principle, attempt to justify a large clearcut on the basis that such large disturbances are natural in their forest. At the scale of the larger landscape, however, the sum or cumulative effect of the individual clearcuts of that size might be very "unnatural."

The problem of relating fire disturbance regime to age distribution is further complicated by apparent age dependency of fire ignition and fire growth. Johnson and Van Wagner (1985) used the Weibull distribution in the analysis of age distributions in such cases. We have not tested age-dependent ignition and growth in FLAP-X, but we believe that if so modified, FLAP-X would demonstrate Johnson and Van Wagner's (1985) results. Specifically, the theoretical age distribution would be an S-shaped variation of the exponential with more area in younger ages, and less in older ages. We also believe that the high degree of variability would still occur in the revised version.

Acknowledgements and Notes

This research was funded by the Ontario Forest Research Institute, and the Natural Sciences and Engineering Research Council of Canada through Operating Grant OGP0004125 to D.L. Martell. FLAP-X runs on current PC compatible microcomputers, and will be available from the Ontario Forest Research Institute. The opinions expressed here are those of the authors and do not necessarily represent those of the Ontario Forest Research Institute or the Ontario Ministry of Natural Resources.

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