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UNIVERSITY OF ALBERTA

UNDERSTANDING AGE-CLASS DISTRIBUTIONS IN THE SOUTHERN CANADIAN ROCKIES

BY

Marie-Pierre Rogeau ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science.

DEPARTMENT OF FOREST SCIENCE

Edmonton, Alberta

Spring 1996

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled UNDERSTANDING AGE-CLASS DISTRIBUTIONS IN THE SOUTHERN CANADIAN ROCKIES submitted by MARIE-PIERRE ROGEAU in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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19 March 1996

A mes parents

ABSTRACT

The purpose of this research was to examine a new approach to understanding and predicting the role of fire in specific ecosystems, in particular mountainous ecosystems. Through documented and simulated fire survivorship (time-since-fire) distributions, the accuracy of the Weibull model, which has been used to understand the historical role of fire in an area, was tested and evaluated. Real time-since-fire data of the Canadian Rockies were used to verify the ability of the model to estimate the fire cycle in mountainous areas. The large size of this fire history database allowed for division of the study area into smaller portions to assess the magnitude of variation of survivorship patterns within the ecosystem. A fire regime simulation program was also designed to model different types of fire regimes. The computer program produced time-since-fire (survivorship) data and kept track of the number and original size of fires before they were burned over by subsequent fires. This last feature was essential to calculate the "real" fire cycle, which was needed to evaluate the ability of the Weibull model to estimate the fire cycle of the simulated fire regimes. Testing of the Weibull model was accomplished by modelling three types of fire regimes which resembled the regimes of the boreal forest under fire suppression, the mountain regions under partial fire suppression, and the mountain regions without fire suppression. The numerous simulated survivorship curves that were produced served as a means for assessing the magnitude of variation of the time-since-fire distributions. Results showed that the Weibull fire cycle calculated for real time-since-fire data of the Canadian Rockies was falsely represented due to spatial variation of the fire cycle over the landscape. The Weibull model was also unable to estimate the fire cycle for the small size areas, and significant variation

in survivorship patterns was found within one ecosystem. Simulations suggested that the present-day survivorship distribution was not representative of the fire regime of an area. The great magnitude of variation encountered in the simulated survivorship distributions, even though the probability of fire occurrence was random and held constant, concluded that changes in the slope of a survivorship distribution should be expected. Thus, a change in slope should not be interpreted as a change in the fire regime. The Weibull model could estimate the true fire cycle within 25 years only for study areas respecting, in all aspects, the assumptions and criteria defined by the Weibull model.

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The creation of the time-since-fire maps could not have been accomplished without the help of several people. I would like to extend my appreciation to David Gilbride for his friendship and support, and who dedicated a great part of his work time to this project from 1991 to 1994. The following Park staff, students and volunteers deserve particular acknowledgement for their assistance with field work and data preparation: Carl Cibart, Jim Dagg, John Groeneveld, Ian Pengally, Gordon Irwin, Anand Pandarinath, Darren Dancy, Elske Van Essen, Bjorn Prenzel, Tom Gilmore, Vlado Vancura, Jack Wierzchowski, Mark Heathcott, Bryan Lee and Henning Barth. Over the years many other people were involved in the field research in one way or another and I am grateful for their assistance. I also thank Gail Moir, GIS consultant, for the labourious task of digitizing the fire history maps.

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CHAPTER I

Introduction

1.1 General

Canadian National Parks' managers have the responsibility of maintaining naturally occurring processes such as fire (Parks Canada 1988). Fire regulates the structure and composition of the vegetation in many temperate plant communities by creating a landscape level patchwork of different aged forest stands, which ensures plant and animal diversity as well as the stability of the ecosystem (Kozlowski and Ahlgren 1974). This form of landscape disturbance is difficult to manage safely with minimal human intervention as stipulated by Parks Canada Policy (Canadian Heritage 1994) because of the nature of fire. Additionally, Parks Canada policies state that all fires must be contained or suppressed if they pose a possible threat to major park facilities, public health or safety, or if it is likely that they may have a serious impact on neighbouring lands (Canadian Heritage 1994). To date, as a result of such policies, fires have not been allowed to burn freely within areas managed by Parks Canada.

In all of the well developed parks, sophisticated approaches to fire detection and suppression have reduced the area burned annually. For example, Banff National Park has not experienced a large wildfire in almost 60 years (White 1985, Rogeau and Gilbride 1994). The same trend can be found in the other western Parks. This reduction of burning is causing the forest age-class distribution to shift towards older age stands. In order to ensure the ecological integrity[1] of the ecosystem, an outcome sought by park managers (Canadian Heritage 1994), fire is being reintroduced through prescribed burning.

The implementation of fire management policies that mimic as closely as possible the natural role of fire requires an understanding of the historical fire regime for the region and the factors that regulate the size, frequency and intensity of fires. It is well known, that the frequency of burning and its effects are influenced by a number of variables such as topography, weather, the composition of the pre-burn plant communities and time of year (Barrows 1951, Alexander and Sandberg 1976, Stokes and Dieterich 1980, Mooney *et. al.* 1981). Fire history studies have been the primary technique for learning about the fire regime of a specific ecosystem.

Previous fire history studies have reconstructed past fire events of an area by using such evidence as (1) fire scars (Arno and Sneck 1977), (2) the sudden release in tree-ring growth patterns (Lorimer 1985, Johnson and Gutsell 1994), (3) the age of forest stands (Tande 1979, Masters 1990, Tymstra 1991), and; (4) recorded information (diary of old explorers, old newspapers accounts, fire reports maintained by fire protection/management agencies). Different methods exist to interpret fire history data. Some are designed to estimate the *fire frequency* - number of fires per unit time in a designated area - or the *fire interval* - number of years between two successive fires in a designated area[2]-, which are frequently used for areas smaller than 3,500 ha (Arno and Sneck 1977, Kilgore and Taylor

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[1] Ecological integrity advocates the preservation of the ecosystem in its pristine state (Canadian Heritage 1994).

[2] Fire terminology can be found in Romme (1981).

1979, Ahlstrand 1980); while others, which are usually used for much larger study areas, have relied on time-since-fire mapping techniques to estimate the *fire frequency* and *fire cycle* of an area (Heinselman 1973, Masters 1990, Johnson and Larsen 1991). The *fire cycle*, which is an important concept of this study, has been defined by Van Wagner (1978) and by Romme (1981) as the time required to burn an area equal in size to the study area, knowing that some areas may burn more than once, while others may not burn at all. Mapping the forested stands by age and area, which is also known as "stand origin" or "time-since-fire" mapping, is considered to be the most appropriate method for uncovering the natural occurrence of fire in subalpine and boreal environments. This is largely because the fire regime of these areas is mainly governed by large, infrequent, high intensity fires (White 1985, Johnson and Wowchuck 1993), which tend to destroy previous fire evidence such as fire scars (Tande 1979). These fires are commonly referred to as "stand-replacing fires". Fire scars in the subalpine environments are scarce, and double or triple scarred trees are extremely rare. Consequently, it is difficult to use the fire history methods described by Arno and Sneck (1977), which were mainly designed for areas where there is an abundance of trees with single or multiple fire scars (Arno *et. al.* 1995).

The time-since-fire mapping technique overcomes this problem of no fire scars by mapping forested areas of the same age, which are known or believed to have originated after fire (Figure 1.1). The time-since-fire map allows users to compute surface areas of stands of similar age-classes (Table 1.1), and to plot the age-class distribution as shown in Figure 1.2. The age-class distribution can also be plotted cumulatively by using the percent of area occupied by each age-class as calculated in Table 1.1. Figure 1.3 presents the cumulated age-

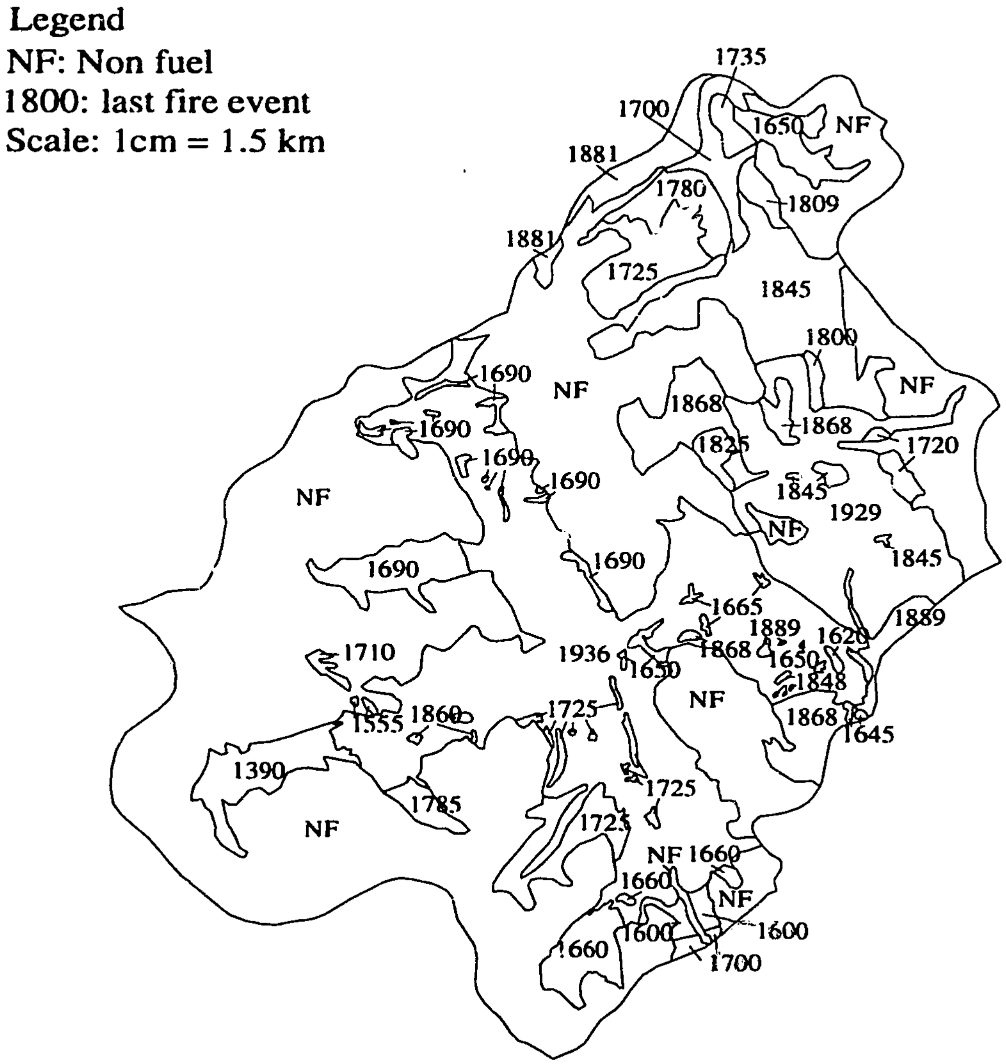

Figure 1.1 Time-since-fire map of Flints Park, Wigmore and Cuthead watersheds, Banff National Park, Alberta.

Table 1.1 A simulated time-since-fire data set before analysis using the Weibull model.

Classes of stand ages	Surface area	Percent of area	Cumulative % of area
10	1243	0.0437	1.0000
20	6078	0.2135	0.9563
30	419	0.0147	0.7428
40	715	0.0251	0.7281
50	265	0.0093	0.7030
60	693	0.0243	0.6936
70	563	0.0198	0.6693
80	1590	0.0559	0.6495
90	1432	0.0503	0.5937
100	36	0.0013	0.5434
110	1715	0.0603	0.5421
120	2889	0.1015	0.4818
130	226	0.0079	0.3803
140	102	0.0036	0.3724
150	636	0.0223	0.3688
160	721	0.0253	0.3465
170	565	0.0198	0.3211
180	32	0.0011	0.3013
190	99	0.0035	0.3002
200	1321	0.0464	0.2967
210	1848	0.0649	0.2503
230	621	0.0218	0.1854
250	353	0.0124	0.1635
270	762	0.0268	0.1511
280	177	0.0062	0.1244
300	98	0.0034	0.1181
310	642	0.0226	0.1147
330	35	0.0012	0.0922
340	478	0.0168	0.0909
350	88	0.0031	0.0741
360	830	0.0292	0.0710
370	6	0.0002	0.0419
380	203	0.0071	0.0417
420	117	0.0041	0.0345
430	470	0.0165	0.0304
440	306	0.0108	0.0139
460	76	0.0027	0.0032
480	14	0.0005	0.0005
Total:	28464	1.0000	

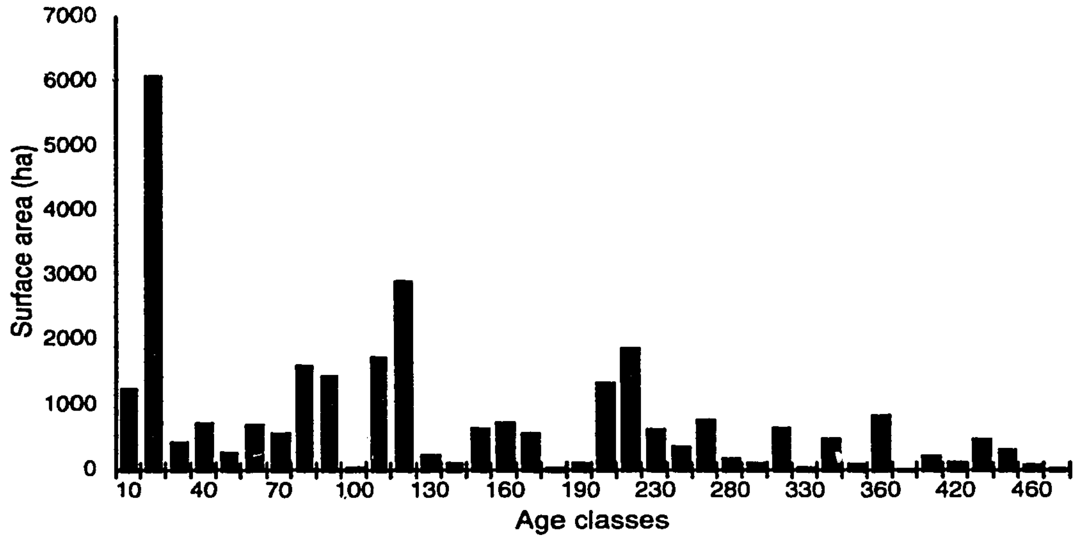

Figure 1.2 Age-class distribution of simulated data (Table 1) represented by size (surface area) of forest stands plotted by 10-year-age-classes.

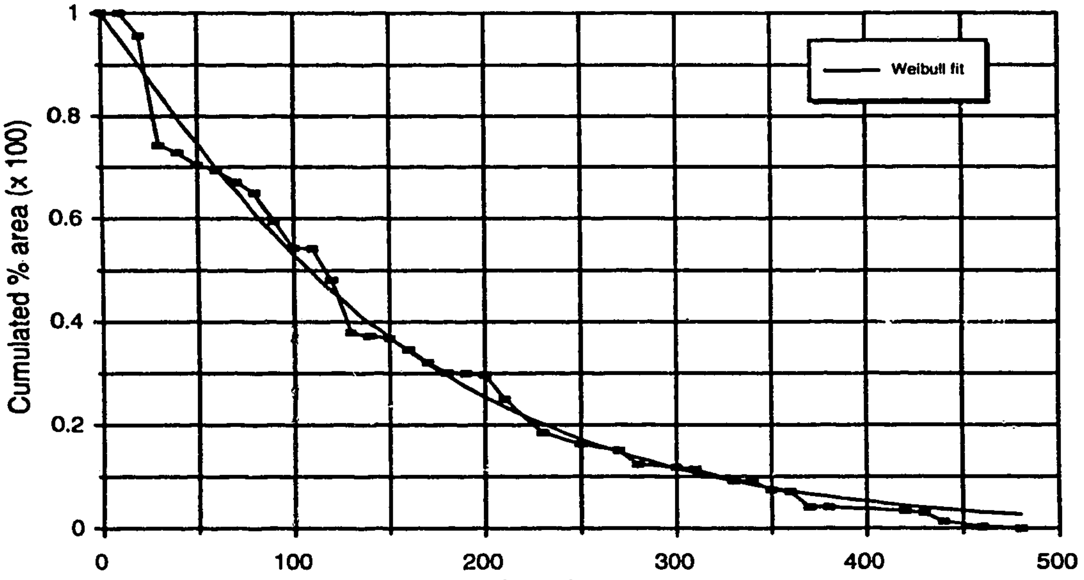

Figure 1.3 Cumulated age-class distribution from the data in Table 1. This curve is known as the time-since-fire distribution. The distribution is represented by cumulatively plotting the percent of stand area by 10-year-age-classes.

Figure 1.4 Cumulated age-class distribution (time-since-fire distribution) plotted on semi-log paper masks small deviations in the distribution of Figure 3, when plotted on regular graph paper.

class distribution for this time-since-fire data set. This distribution is also referred to as the *time-since-fire distribution* or the *survivorship distribution* (Johnson and Gutsell 1994). The time-since-fire distribution is commonly plotted on a semi-logarithmic scale to linearize and mask small deviations (noise) in the distribution (Figure 1.4). The Weibull function has been used to model this cumulative distribution and to calculate the fire cycle (Johnson *et. al.* 1990, Masters 1990, Johnson and Larsen 1991).

The *fire cycle* is frequently used by forest and park managers as a decision making tool. The inverse of the *fire cycle* is, in theory, the average percent of area that historically burned annually in a management unit (Johnson and Van Wagner 1985). This measure is used to estimate the average amount of land that should be burned annually in order to sustain the natural fire cycle and hence, the diversity common to the natural forest age structure for the area.

In studies conducted over the past 15 years, the fire cycle has been estimated using the Weibull model or a special case of the Weibull, the negative exponential (Van Wagner 1978, Johnson 1979, Johnson and Van Wagner 1985, Johnson and Gutsell 1994). The Weibull and negative exponential models are used to model time-since-fire data, which has been converted to a time-since-fire distribution (Johnson and Gutsell 1994). These models were originally adopted to represent the historical occurrence of natural fires within large areas (> 40,000 km^2) of the boreal forest (Van Wagner 1978, Johnson 1979). More recently, the negative exponential model has been applied to several smaller fire history study areas in the subalpine forest of the southern Canadian Rockies (Johnson *et. al.* 1990, Masters 1990, Johnson and Larsen 1991, Tymstra 1991). The authors of the fire history models believe that the fire cycle, when calculated with those models, is equal or closely related to the average age of the forest.

The problem associated with time-since-fire models is that they have never been validated due to the overlapping nature of fires. It is well known that with repeated burning, evidence or boundaries of previous burn areas may be greatly reduced or lost. For example, an 1820 fire originated-stand, mapped as 500 ha in 1995, could originally have been as big as several thousands hectares but the boundaries of the original area have been masked by subsequent fires. Hence, the actual fire cycle of an area is unknown, and it is impossible to reconstruct it using time-since-fire data. In addition, the effect of study area size in relation to fire size distribution is not well understood.

1.2 Fire history models

The historical role of fire in an area has traditionally been explained using the negative exponential and Weibull models. A description of these models and their equations, as well as the assumptions required to use such models, is summarized in this section for the convenience of the reader.

The Weibull and negative exponential functions have been adequately described by Lawless (1982), Johnson (1979), Van Wagner (1978), Johnson and Van Wagner (1985) or Johnson and Gutsell (1994). These models have been used extensively in the analysis of "lifetime" data (Lawless 1982). Among other lifetime models such as the gamma, beta, log normal and extreme value (Hahn and Shapiro 1967), to name only a few, the Weibull and negative exponential models remained the most appropriate for analysis of "survivorship" of forest stands relative to stand replacing disturbances such as fire (Johnson 1979). The Weibull "time-since-fire distribution model", or "survivorship distribution", has been defined by Johnson and Gutsell (1994) as:

$$A(t) = \exp(-(t/b)^c) \qquad \textbf{[1.1]}$$

The scale parameter b is the expected recurrence time of fire (years), t is the age of forest stands and c is a dimensionless shape parameter. Depending on the application, c will vary but for time-since-fire data, the shape value c will commonly range between 1 and 4 (Figure 1.5). The shape parameter c of the Weibull model is thought to account for the change in the risk of burning. It is generally assumed that a distribution with $c > 1$ portrays a risk of burning that increases over time, or as forest ages, while $c < 1$ represents a decrease in the risk of burning with age. When $c = 1$, the distribution pattern is best modelled using the negative exponential. Van Wagner (1978) and Johnson and Gutsell (1994) suggest that for this case the risk of burning is constant over time, and fire occurrence is a random event. It should be remembered that the negative exponential is simply a special case (or form) of the Weibull model (Figure 1.5).

The reason for using the Weibull function as a fire history model, is that it is believed that the reoccurrence of historical fire events are reflected in the actual age-class distribution of forest stands (Van Wagner 1978). It has been repeatedly shown that Equation 1.1 models well most time-since-fire distribution patterns (Masters 1990, Johnson and Larsen 1991). Also, the parameters obtained during the fitting of the model to the age-class distribution, can be used in Equation 1.2, as discussed in Johnson and Gutsell (1994), to calculate the fire cycle.

$$\textit{Weibull fire cycle} = b\Gamma[\frac{1}{c}+1] \qquad \textbf{[1.2]}$$

It should be noted that for the negative exponential model, where $c = 1$, the Weibull fire cycle is simply equal to b.

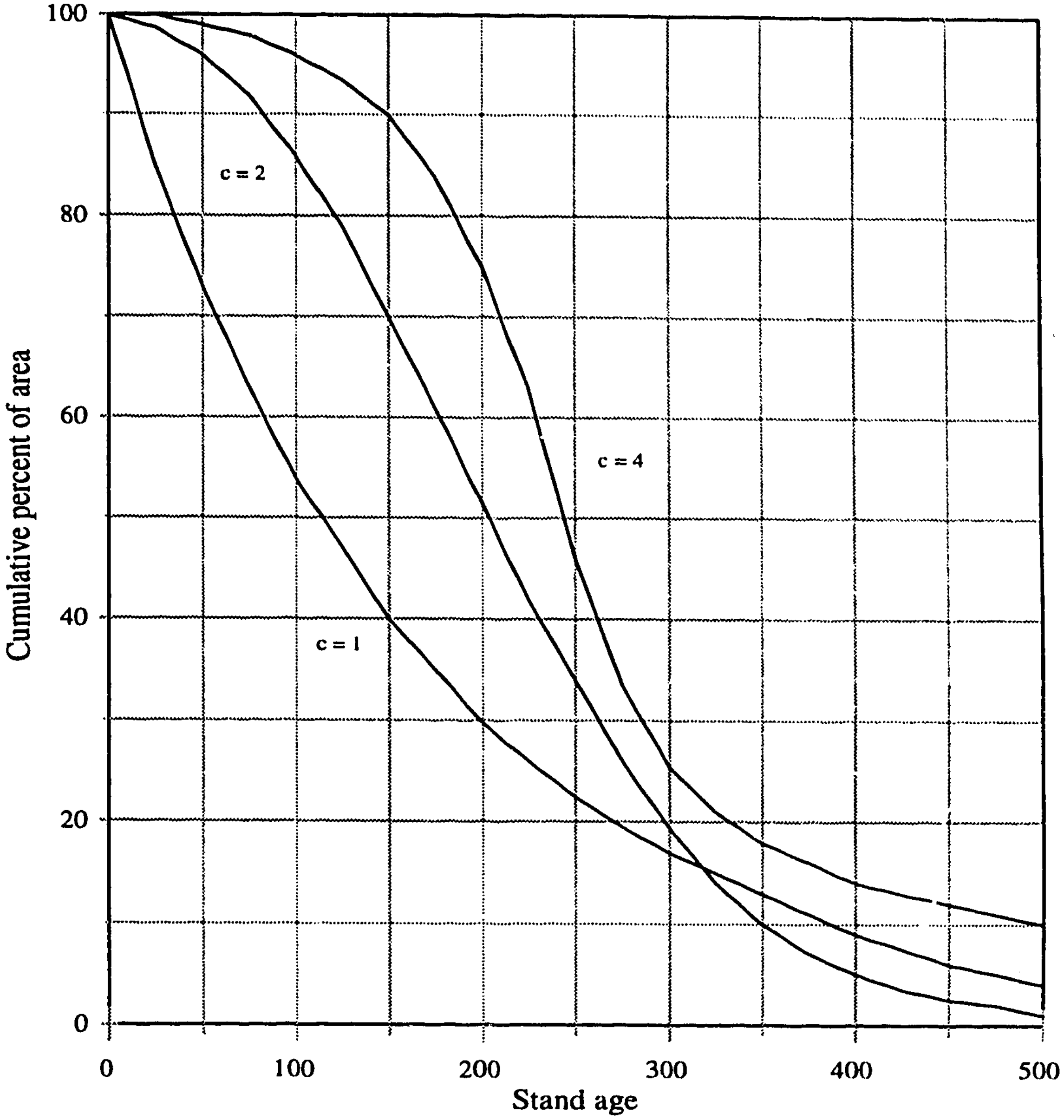

Figure 1.5 The Weibull survivorship distribution function. The shape (c) of a distribution for time-since-fire data will usually range between 1 and 4. When c = 1, the distribution plots as a negative exponential.

The negative exponential distribution is sometimes preferred when modelling time-since-fire patterns based on cumulated age-class distribution data, because it involves the use of only one parameter (scale) and data can be plotted as a descending straight line on semi-logarithmic paper (Van Wagner 1978). Also, the relative ease in calculating the fire cycle, which simply consists of a linear regression analysis and the calculation of the inverse of the slope of the line of best fit, makes this simpler distribution extremely popular. However, this model is based on the assumption that the risk of burning must be constant over space and time. Additionally, it must be assumed that the age of the forest does not influence the probability of burning (Johnson and Larsen 1991). Previous fire history studies have shown that data from the Canadian Rockies produce time-since-fire curves that are relatively well fitted by a negative exponential distribution (Johnson *et. al.* 1990, Masters 1990, Johnson and Larsen 1991).

Van Wagner (1978) demonstrated, through fire modelling, two important properties of the negative exponential model: (1) the fire cycle (the inverse of the slope of the line of best fit) equals the mean age of the forest, and (2) 63.2% of all stands are younger than the mean age. Hence, he concluded the probability of a stand surviving throughout an entire fire cycle to be 36.8%. His findings agreed with the assumption that fire occurrence is random across an area and that some landscape units burn more than once while others not at all.

Since it was demonstrated that the fire cycle is equal to the mean forest age or "*b*" for the negative exponential model, one can assume that the fire cycle of the Weibull model portrays something close to the mean forest age as well. This is due to the fact that the parameter "*b*" of the Weibull fire cycle equation (Equation 1.2) is multiplied by a constant, which is the gamma function of 1/c + 1, that ranges normally between 0.9 and 1.1 for shape values (*c*) ranging between 0.8 and 4. These shape values are common to time-since-fire distributions. Although, for the fire history models to adequately predict the fire cycle or the mean forest age, several assumptions and criteria must be respected, as described in the next section.

Assumptions and criteria

When developing a fire history for an area where ages of stands are used in the absence of fire evidence, one must assume that fire was the only disturbing agent responsible for forest stand replacement. It must also be assumed that stands initiated immediately after fire, or that there was no significant time-lag in tree establishment and survival. Johnson and Van Wagner (1985) stipulate that "The negative exponential and Weibull models apply to homogeneous stochastic processes" (p. 216). These authors believe that homogeneity is reflected by two important criteria of stability: (1) the area of interest must be under a similar fire regime, (2) the fire regime must be constant on average over the range of years covered by the fire history data. Another important criteria specifies the minimum size of the study area. As a rule of thumb, the largest possible fire occurring, or burn area in one fire year, should not exceed one third of the total surface of the study area (Johnson and Gutsell 1994). Additionally, the fire cycle should also be small in comparison to the time period of the fire history study. Johnson and Van Wagner (1985) suggest studies that span time periods longer than 400 years may have been affected by climatic changes, which are likely to occur over such a time period. They further suggest that a change in climate might be reflected by a change of slope in the age-class distribution of the sampled population.

1.3 Research incentive

As part of an extensive fire history study in the southern Canadian Rockies, which took place in Banff National Park (Rogeau and Gilbride 1994) and Mount Assiniboine Provincial Park, British-Columbia (Rogeau 1994), the methods commonly used to analyse fire history data were re-evaluated. Banff National Park encompasses 6,287 km^2 of land while Mount Assiniboine covers 208 km^2 of land for a total of 6,495 km^2. The time-since-fire database, which was recently compiled for this region, is one of the largest in North America.

The goal of this study was to test the ability of the Weibull fire history model to capture the historical frequency of fire in this ecosystem. Even though the Weibull model has been used for several fire history studies located in the Canadian Rockies (Johnson et. al 1990, Masters 1990, Johnson and Larsen 1991, Tymstra 1991), a preliminary analysis of the Banff fire history data raised questions about the assumptions and the logic for using it. Specifically, limitations in the method used for sampling impede on our ability to plot accurately the tail of the distribution. When sampling for fire history data, tree life expectancy does not allow us to date burns older than about 300 to 500 years. The inherent problem with old age stands, those usually older than 300 years, is that only a limited number of those stands have supporting and datable evidence of fire. When fire evidence is not available, such as fire scarred tree or historical record, the current practice is to use the oldest tree sampled as the estimate of the age of the stand. This practice should be questioned because there is a possibility that the fire event could have occurred anywhere from 20 or more years prior to the date of the oldest tree (Johnson and Larsen 1991, Rogeau and Gilbride 1994). Basically, reconstructing past fire events in stands older than 300 to 350[3] years is often imprecise because the date is based on the oldest tree found, and because fire boundaries within old age stands are not discernable. The stand could possibly encompass more than one burning event.

Homogeneity in the fire regime of mountain regions is also an issue. Terrain features, such as aspect, slope steepness, elevation and valley orientation to prevailing winds are also known to affect the local fire regime (Barrows 1951) and impact on fire frequency, its distribution and pattern. Therefore, a failure to respect the criteria of homogeneity could directly impact on the ability of the Weibull function to estimate the fire cycle.

In addition, in light of the fact that the study of fire regimes is relatively new and that time-since-fire distributions, as defined by Johnson and Gutsell (1994), are not available for every year or decade, especially before the recent impact of human technology on fire detection and suppression, it is not possible to know the magnitude of variation within the time-since-fire distribution pattern. Therefore, is it legitimate to assume that the present-day time-since-fire distribution is similar to what would have been found 300 or 150 or even 75 years ago? Our knowledge of forest survivorship to fire in a specific area is based, in most cases, on one time-since-fire curve, which really amounts to a sample of one. This problem must be investigated to determine the suitability of the present-day time-since-fire

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[3] This number will vary based on the forest community type and environmental conditions of the stand.

distribution as a means of understanding the fire regime. It follows that the value of this information should be questioned before using it for fire and forest management purposes. In contrast and by way of example, the expected mortality rate, or survivorship rate, for different age groups within the human population is fairly reliable due to numerous years of statistics documenting the number of deaths by age-classes as the cohorts of these age groups proceed through time. Figure 1.6 provides an example of fictitious survivorship distributions recorded over a seven year period. Those distributions are informative as they provide a mean survival rate per age-class, with its fluctuation over the years. Therefore, it could appear that the Weibull and negative exponential distributions, used as a time-since-fire models, could be misleading in the interpretation of forest survivorship to fire.

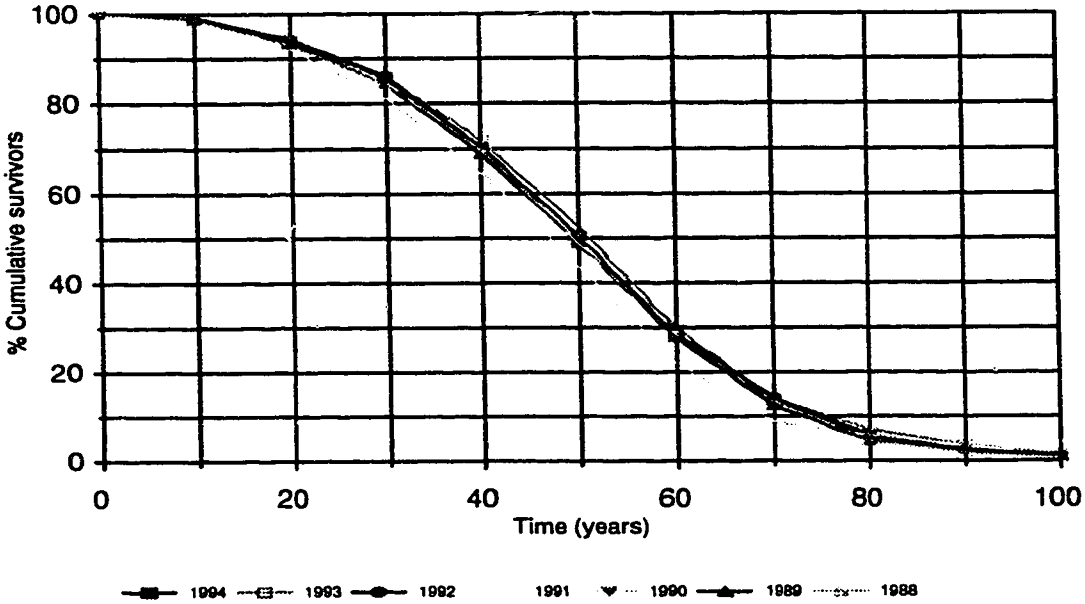

Figure 1.6 Example of a yearly survivorship distribution (fictitious data).

1.4 Objectives

The purpose of this thesis is to propose a new approach to understanding and predicting the role of fire in specific ecosystems. The objectives were:

1) To evaluate the magnitude of spatial variation of the present-day age-class distribution, and to assess the ability of the Weibull model to estimate the fire cycle for actual time-since-fire distributions of two parks in the southern Rocky mountain ecosystem.

2) To evaluate some of the critical criteria required by the model, and to assess the ability of the Weibull model to estimate the fire cycle for simulated age-class distributions under different fire regimes.

1.5 Study design and thesis layout

This thesis was written in a chapter format to separate the large amount of information presented. In chapter 2, real time-since-fire data of the Canadian Rockies, specifically for Banff National Park and Mount Assiniboine Provincial Park (Rogeau 1994, Rogeau and Gilbride 1994), were analysed. The goal of this study was to verify if the Weibull model can be applied to mountainous areas. Also, the large size of Banff National Park (6,287 km^2 wherein over 3,000 km^2 is forested) allowed for division of the study area in smaller portions (watersheds) to assess the ability of the Weibull model to estimate the fire cycle, or the average age of the forest, for smaller areas. Lastly, as part of this study, the magnitude of variation of the time-since-fire distribution within the ecosystem, as suggested by Johnson and Gutsell (1994), was evaluated.

In chapter 3, an approach that allows for greater in depth testing of the Weibull model is presented. This was accomplished by designing a fire regime simulation program that predicts time-since-fire maps and age-class distributions of real data from the boreal and mountain environments. Simulated time-since-fire curves also provided a means for assessing the magnitude of variation of these distributions. The computer program was designed to simulate time-since-fire data and to keep track of the number and original size of fires before being over burned by subsequent fires. This last feature was essential to calculate the "true" fire cycle for the simulated distributions in an attempt to evaluate the ability of the Weibull model to estimate the fire cycle for the same distributions. The true fire cycle refers to a fire cycle calculated for the simulations and should not be confused with a "real life fire cycle", which is at present impossible to calculate.

In chapter 4, the conclusions found in Chapters 2 and 3 are summarized. My opinions on future research needs are presented in the fifth and last Chapter.

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CHAPTER II

Spatial variation of age-class distributions in the Southern Rocky Mountains of Canada

2.1 Introduction

Fire regulates the structure and composition of the vegetation in many temperate plant communities by creating a landscape level patchwork of different aged forest stands. Most ecologists would agree that this ensures plant and animal diversity as well as the stability of the ecosystem. This century however, sophisticated approaches to fire detection and suppression have resulted in a reduction of the surface area burned annually. For example, Banff National Park has not experienced a large wildfire in almost 60 years (White 1985, Rogeau and Gilbride 1994). This reduction in burning is causing the forest age-class distribution to shift toward older age stands. This change is perceived to be unnatural and a threat to the ecological integrity[1] of the ecosystem, an outcome sought by park managers (Canadian Heritage 1994). In an effort to reverse this trend, fire has been reintroduced in this Park through prescribed burning.

The implementation of prescribed burning programs or other fire management policies that allow for a more natural role of fire within National Parks (Parks Canada 1988) requires an understanding of the historical fire regime for the region. Specifically, managers need to know if the size, frequency and intensity of fires vary by geographical area or within time periods. It is well known that the frequency of burning and its effects are influenced by a number of variables such as topography, weather, the composition of the pre-burn plant

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[1] Ecological integrity advocates the preservation of the ecosystem in its pristine state (Canadian Heritage 1994).

communities and time of year (Barrows 1951, Alexander and Sandberg 1976, Stokes and Dieterich 1980, Mooney *et. al.* 1981). Fire history studies have been the primary technique for learning about the fire regime of a specific ecosystem.

The negative exponential model, which is a special case of the Weibull model, has traditionally been applied to fire history data from studies of the Canadian Rockies. Specifically, this model has been used to interpret the fire survivorship pattern of forest stands in Kootenay (Masters 1990), Glacier (Johnson *et. al.* 1990) and Yoho (Tymstra 1991) National Parks, and Kananaskis Country (Johnson and Larsen 1991). This model was chosen because it is assumed that stand age does not affect the probability of burning and that fire distribution is therefore random over the landscape. However, in all of these studies, the time-since-fire (survivorship) distributions showed changes in slope, which have been interpreted as a change in the fire regime.

The traditional solution to this "mixed" distribution is to partition fire history data into homogeneous distributions by separating data into spatial characteristics (i.e. by aspect, elevation or valley orientation), and temporally, if the spatial partitioning fails to stratify the data into distinct (statistically different) homogenous distributions (Johnson and Gutsell 1994). With the exception of Tymstra (1991), who found a difference in the fire cycle between the eastern and western portions of his study area, the other researchers had to stratify their data temporally in order to obtain homogeneous time-since-fire distributions. In all cases, it was argued, but without supporting evidence, that a climate change was responsible for the heterogeneity experienced in the age-class distribution.

The degree of heterogeneity in the data sets of those mountain regions could be partly due to the fact that some of the assumptions and criteria, which are required to use the model, were violated (Johnson and Van Wagner 1978, Johnson and Gutsell 1994). The Weibull model was originally applied to large areas of the boreal forest where terrain is relatively uniform (Van Wagner 1978, Johnson 1979). In mountainous areas, the primary assumption of homogeneity is usually not satisfied due to the effect of terrain (aspect, elevation, valley orientation to prevailing winds) on ignition, fire growth patterns, fuel moisture and fuel availability. Furthermore, the fire regime is affected by the frequency and distribution of lightning strikes, which are highly variable in the mountains (Barrows 1951, Kourtz 1967, Van Wagtendonk 1991). Lightning distribution over Banff National Park was found to be uneven, and areas with a low probability of ignitions seem to coincide with areas of older forest (unpublished data, Banff National Park). Therefore, the assumption of random spatial distribution of fires is likely not supported in mountainous terrain and could yield to a distribution that is not negative exponential.

By spatially partitioning time-since-fire distributions (Johnson *et. al.* 1990, Masters 1990, Johnson and Larsen 1991), the criteria with respect to using a sufficiently large study area was not likely met. Most of these study areas only contain one main valley with a single orientation. Once divided by elevation or aspect classes or even by valley orientation, the area attributed to each topographic class may not have been big enough to contain a representative sample of age classes which seems to be a requirement to be properly fitted by the Weibull or negative exponential model (Johnson and Van Wagner 1985, Johnson and Gutsell 1994). Perhaps the violation of some of the assumptions and criteria were the cause for failing to obtain homogenous spatial partitions.

Another inherent problem in this approach is that the study of fire regimes is relatively new and that survivorship distributions are not available for every year or decade, especially before the recent impact of human technology on fire detection and suppression. In light of this fact, it is not possible to know the magnitude of variation of the time-since-fire distribution. Therefore, is it legitimate to assume that the present-day survivorship distribution was similar to 300 or 150 or even 75 years ago? Our knowledge of forest survivorship to fire in a specific area is based in most cases on one survivorship curve. In reality, this amounts to a sample of one. This problem must be investigated to determine the suitability of the present-day survivorship distribution as a means of understanding the fire regime. It follows that the value of this information should be questioned before using it for fire and forest management purposes.

Lastly, limitations in the method used for data sampling impede our ability to plot accurately the tail of the distribution. When sampling for fire history data, tree life expectancy does not allow us to date burns older than about 300 to 500 years. The inherent problem with old age stands, usually older than 300 years, is that only a limited number of those stands have supporting and datable evidence of fire. When fire evidence is not available, it is current practice to age those stands by using the oldest tree sampled, even though there is a possibility that the fire event occurred anywhere from 20 or 300 years prior to the date of the oldest tree (Johnson and Larsen 1991, Rogeau and Gilbride 1994).

Basically, reconstructing past fire events in stands older than 300 to 350[2] years is often imprecise because the date is based on the oldest tree found, and because fire boundaries within old age stands are not depicted. The stand could possibly encompass more than one burning event.

In light of all of the problems suggested above, the goal of this study was to test the ability of the Weibull fire history model to capture the historical frequency of fire in Banff National Park and in Mount Assiniboine Provincial Park. The time-since-fire database for these regions is sufficiently large to allow for division of the area into smaller portions which can, in turn, be used to address such concerns as:

1) Should the Weibull model, or its variant the negative exponential model, be applied to mountain areas?

2) How well does the Weibull or negative exponential model fit distributions from smaller areas?

3) How well does the fire cycle, calculated from these models, estimate the average age of the forest of smaller areas?

4) Can smaller landscape units within the study area account for the magnitude of variation of the survivorship distribution that is expected for the whole study area?

2.2 Study area

Banff National Park (BNP) is located in southwestern Alberta, about 100 km west of Calgary (Figure 2.1). The Park encompasses 6,287 km2 of land, of which close to 50%

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[2] This number will vary based on the forest community type and environmental conditions of the stand.

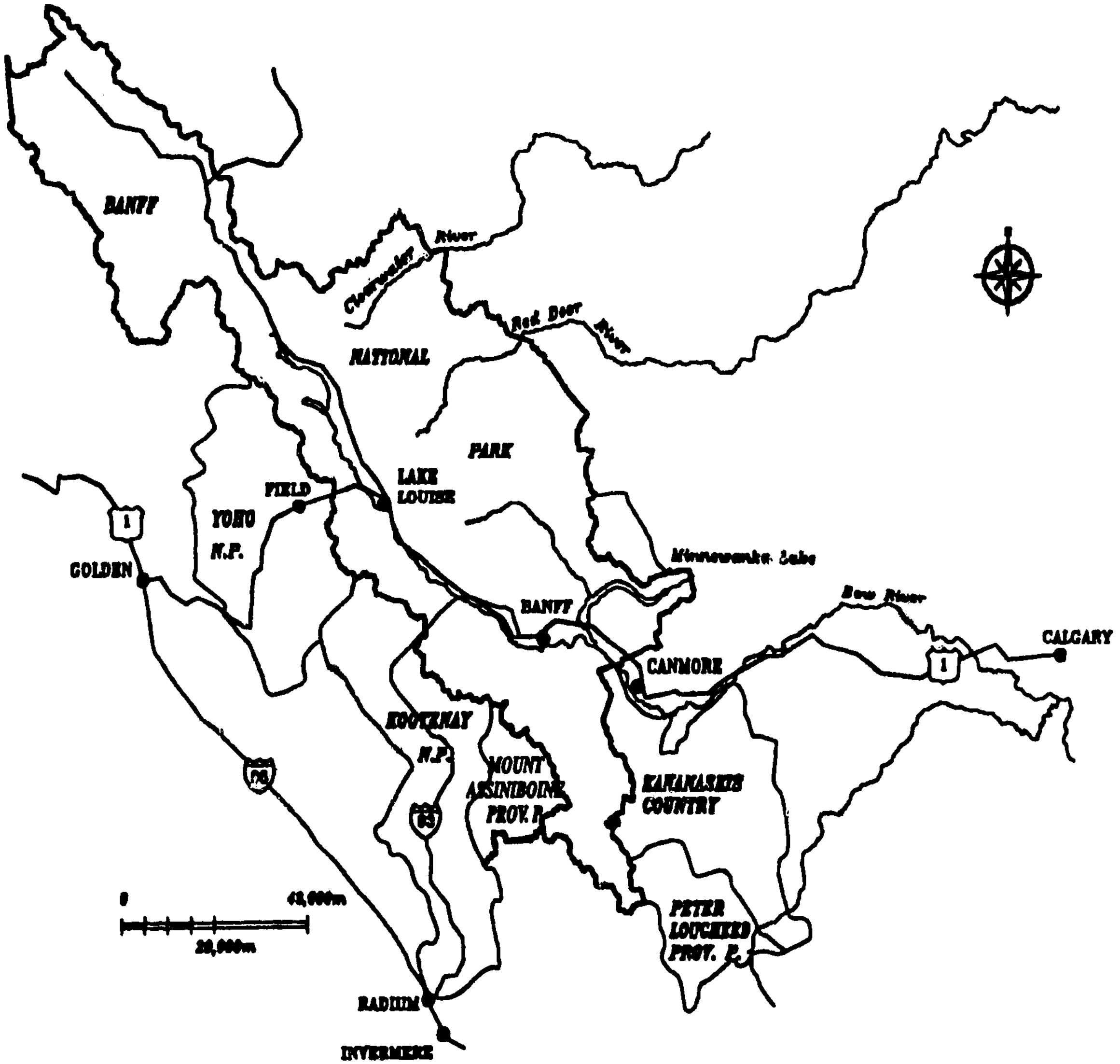

Figure 2.1 Study area: Banff National Park, Alberta and Mount Assiniboine Provincial Park, British-Columbia. Southern Canadian Rockies. (Adapted from J.L. Wierzchowski, 1995)

is composed of rock and ice. The Park is bordered to the west by the Continental Divide, with the main valleys tending to run parallel in a northwest / southeast direction. Mount Assiniboine Provincial Park (MAPP) lies on the west side of the Continental Divide in southeastern British-Columbia and shares a common boundary with BNP. MAPP covers 386 km^2 of land with 54% of this area also covered by rock and ice. The minimum elevations in BNP and MAPP are ±1350m asl. and ±1500m asl., respectively. Both Parks contain some peaks as high as ±4000m asl., and treeline is normally found at approximately 2500m asl.. Four ecoregions characterize the Parks: montane, lower subalpine, upper subalpine and the treeless alpine region.

The forest of this region is mainly composed of lodgepole pine (*Pinus contorta* Loudon[3]) stands, mixed stands of Engelmann spruce (*Picea Engelmannii* Parry) / subalpine-fir (*Abies lasiocarpa* [Hook.] Nutt.) and, at higher elevation, a combination of larch (*Larix lyallii* Parl.) / Engelmann spruce / subalpine fir. At lower elevation in the montane zone, pockets of aspen clones (*Populus tremuloides* Michx.) and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) trees are also common.

The fire regime of this area is mainly governed by large, infrequent, high intensity fires (White 1985, Johnson and Wowchuck 1993), which tend to destroy previous fire evidence such as fire scars. Thus, fire scars in the subalpine environments are scarce, and double or triple scarred trees are extremely rare.

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[3] Moss 1983 serves as the reference for all tree names used in this document.

2.3 Methods

Mapping the forested stands by age and area, which is also known as "stand origin" or "time-since-fire" mapping (Heinselman 1973, Johnson and Gutsell 1994), was used for uncovering the natural occurrence of fire in this subalpine environment. Forest aging for a fire history study is best done by sampling: 1) remnant trees in a burn area, 2) post-fire regenerated trees, and 3) trees along the edges of burns (Arno and Sneck 1977). Potential sample sites and stand boundaries were identified by using black and white air photos at a scale of 1:40 000. Forest stands that were possibly different in age were defined by a change in texture and colour on the image. If the exact location of stand edges was blurred due to bad exposure, shadows, clouds or snow, the ecotones were identified using aerial or ground reconnaissance. The stand boundaries as identified on photographs, were transferred to a 1:50 000 topographical map. This map served as the "base map", which was used to locate and identify the sampling sites. It was also used in the field to adjust the exact location of stand boundaries.

Sample sites were located on both sides of stand boundaries, and additional sites were sampled for large size stands, thus, increasing the probability that multiple burn histories within the stands could be detected. When a stand appeared to be heterogeneous, but ecotones were not visible, additional plots were taken. If there was heterogeneity in the tree species as well, bole samples were taken from dominant and subdominant species. However, in the case of mixed Engelmann spruce (*Picea Engelmannii* Parry) /subalpine-fir *(Abies lasiocarpa* [Hook.] Nutt.) stands, the spruce was preferably chosen over the fir because the latter is considered to be a late seral species and will usually be younger than the spruce (Day

1972, Aplet *et. al.* 1988).

Bole samples consisted of cross-sections and cores, but preference was given to cutting cross-sections as they are more accurate in aging trees (McBride 1983). Cross-sections were taken as close to the ground as possible to reduce the potential error due to a growth time-lag and to avoid missing years of growth (Zackrisson 1981, McBride 1983). However, no factor of correction was applied for germination and growth time-lag as trees do not grow at the same rate due to several factors including genetic and environmental limitations. Cross-sections were always taken from scarred trees and for trees showing a release (Lorimer 1985). A release is a sudden and significant increase in the ring width pattern for a period of at least 10 years. For a release sample, the portion of the cross-section selected always faced the burn area, as this side of the tree is favoured as a result of reduced competition for space and light exposure. Preparation of the cross-sections and cores and the ring counting procedure followed methods described by Arno and Sneck (1977).

Each stand on the time-since-fire map was assigned a stand origin date. All stands were known or believed to have originated after a fire. Dating past fire events in BNP and MAPP consisted of using such evidence as (1) fire scars, (2) the sudden release in tree-ring growth patterns, (3) the age of forest stands, and (4) recorded information (diary of old explorers, old newspaper accounts, fire occurrence reports). The time-since-fire map was entered numerically into a Geographic Information System (GIS) and stored in a format ready for spatial analysis. In the GIS, surface area for stands grouped by 10-year age-classes were obtained. The percent of area for each age-class was calculated and plotted cumulatively in such a way that at time zero, 100% of the study area was covered.

The Weibull function defined by Johnson and Gutsell (1994) as:

$$A(t) = \exp(-(t/b)^c) \qquad [2.1]$$

was used to model the cumulative distribution of BNP and MAPP, and the Chi-square-goodness-of-fit statistic ($X^2_{.05,n-1}$) was calculated for each Park ("n" representing the number of 10-year-age-classes in the distribution). The "non-overlapping landscape unit" method, which was suggested by Johnson and Gutsell (1994), was implemented to assess the magnitude of variation of a survivorship distribution. Thus, Banff National Park was divided into its 43 watersheds, which ranged in size from approximately 950 to 45 000 ha. It seemed likely that several watersheds would be too small to preserve the size criterion required by the Weibull fire history model. Therefore, Banff was also partitioned into its seven main drainage basins, which are: (1) the North-Saskatchewan River (66 589 ha), (2) the Clearwater River (12 084 ha), (3) the Red-Deer River (21 387 ha), (4) the Panther River (12 854 ha), (5) the Upper/Middle-Bow River (97 282 ha), (6) the Lower-Bow River (68 762 ha), which includes the whole southern part of the Park, and, (7) the Cascade River (40 875 ha). For each landscape units, the Chi-square-goodness-of-fit statistic ($X^2_{.05,n-1}$) was calculated as well.

The Weibull fire cycle was calculated with Equation 2.2 (Johnson and Gutsell 1994):

$$\textit{Weibull fire cycle} = b\Gamma[\frac{1}{c} + 1] \qquad [2.2]$$

by using the estimated *b* and *c* parameters as determined from Equation 2.1. This was computed for both Parks and for each landscape unit. The accuracy of the Weibull model on small areas was estimated by the ability of the fire cycle to estimate the average age of the forest. The average age of the forest was simply calculated by multiplying each stand age by its percentage of area and by summing those weighted stand ages. For the purposes of this study, the fire cycle calculated from the Weibull model should be able to predict the average age of the forest within 25 years, and that, 80% of the time. Therefore, the time difference between the Weibull fire cycle and the average age of the forest was also calculated.

To determine if the present-day time-since-fire distribution (survivorship) is a reliable tool for management, the standard deviation around the mean of each age-class was obtained from the landscape unit distributions. Those statistics were calculated for discrete data sets (surface area) and for the cumulated distributions (cumulative % of area). If the standard deviation remains within 10 percent of the mean value, and that is true for 80 percent of the age-classes, then I assume the present-day distribution to be acceptable for management purposes.

2.4 Results

The survivorship distributions for Banff and Mount Assiniboine Parks were well modelled by the Weibull function ($X^2_{.05,51} \approx 68.5$, $X^2 = 44.0$, and $X^2_{.05,24} = 36.42$, $X^2 = 35.21$, respectively). The shape values (c) of the distributions for these two Parks were 1.7 and 1.6, respectively, which suggest these distributions are better modelled by the Weibull form than the negative exponential (Figure 2.2a and 2.3a). However, these shape values were reduced to 1.5 and 1.2 if the stands younger than 50 years of age, which corresponds to the period where fires were heavily suppressed, are removed from the distributions (Figure 2.2b and 2.3b). It should be noted that these survivorship distributions with their relative shape values include stands older than 300 years. Although the ages of these stands may not reflect the actual fire dates, they are the only estimates of age available at present.

. The Weibull fire cycle for BNP was 216 years and was within 8 years of the average age of the forest (208 years). As for MAPP, the Weibull fire cycle and average age of the forest were found to be 266 and 255 years, respectively; or within 11 years. For the time-since-fire distributions without the fire suppression period, the fire cycle of each distribution is reduced by 50 years, which corresponds to the number of years removed from the distribution.

The Weibull model was not able to mimic well the survivorship distribution of many of the landscape units (Appendix A). Of the main drainage basins, the Clearwater, Red-Deer, Lower Bow and Middle Bow river basins were the four drainages best fitted with the expected Weibull distribution. The Chi-square test for the North-Saskatchewan river basin accepted the fit at a lower level of significance of .025, while the Panther and Cascade river basins were found to be well fitted at a low level of significance of .005 and .001, respectively. Despite the poorer fit of some of the main drainage distributions, the Weibull fire cycle was always within 20 years of the average age of the forest. However, 29 distributions from the smaller landscape units (Appendix B) were rejected by the goodness-of-fit test when the confidence level was set at 95%, and the accuracy of the Weibull fire cycle was less than that for the larger drainage basins (Table 2.1). Only 58% of these smaller watersheds had a fire cycle within 25 years of the average age of the forest. Based on a

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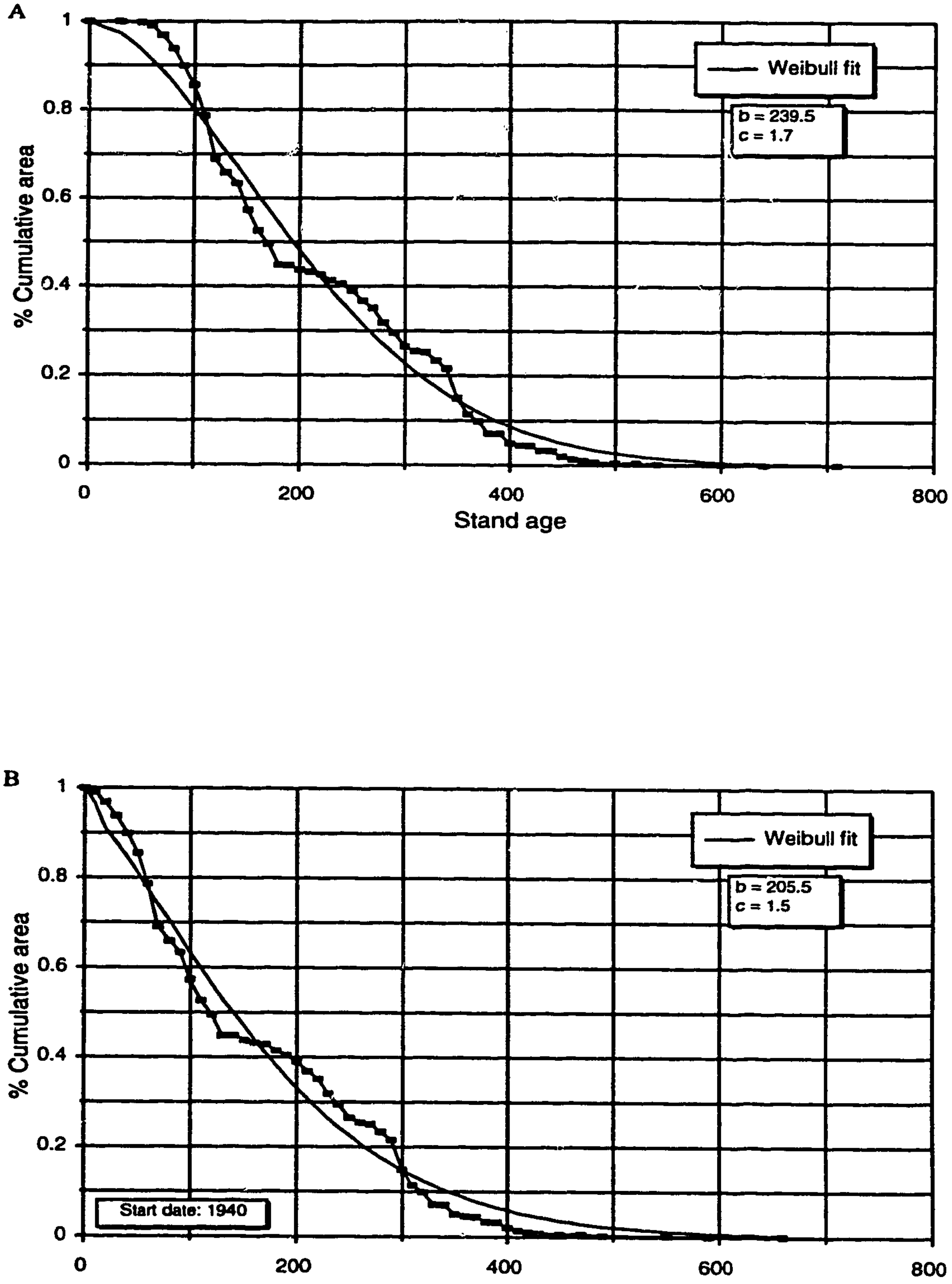

Figure 2.2 Survivorship distribution and its Weibull fit for Banff National Park: A) present-day distribution as of 1990, B) before fire suppression as of 1940.

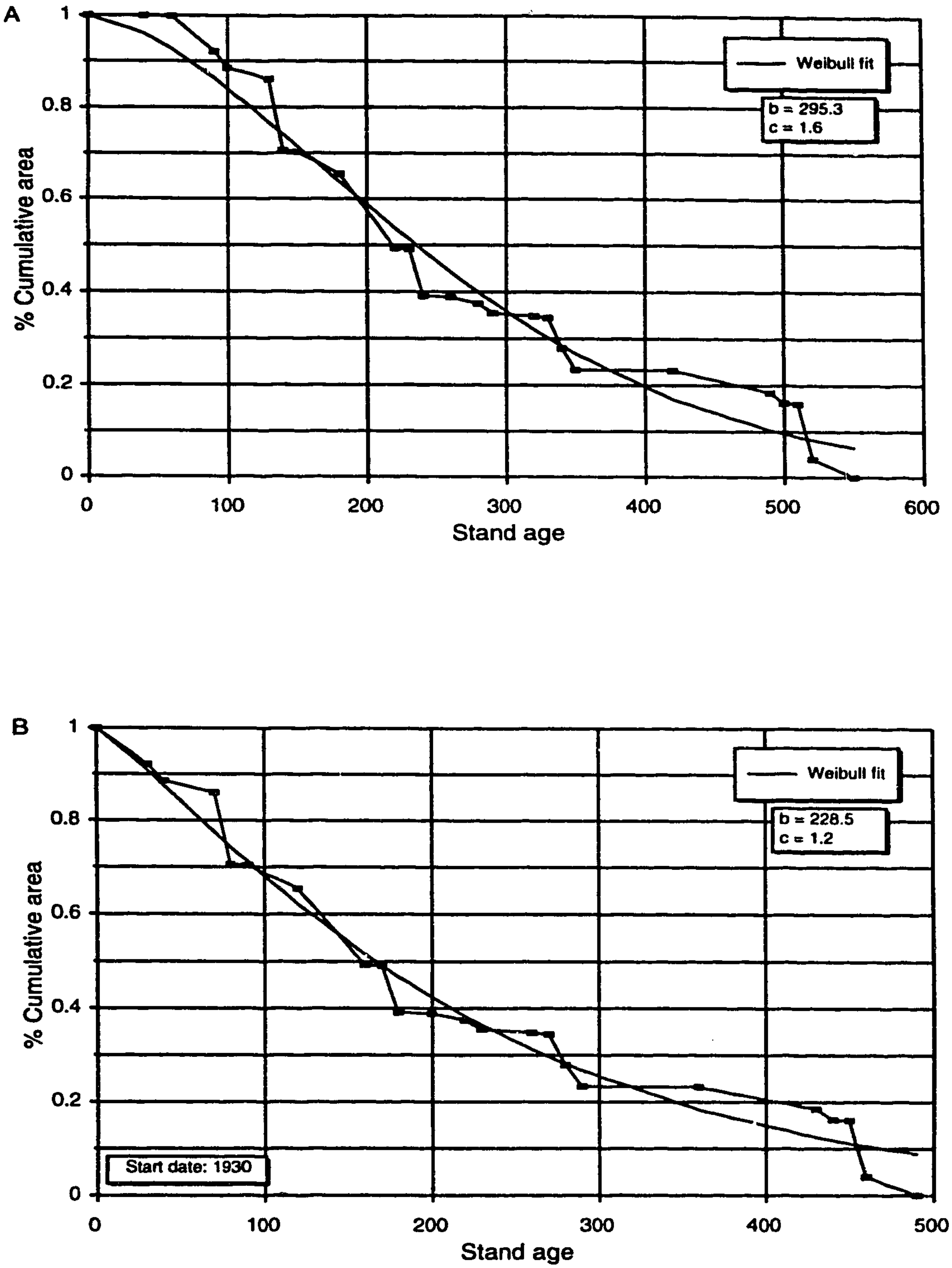

Figure 2.3 Survivorship distribution and its Weibull fit for Mount Assiniboine Provincial Park: A) present-day distribution as of 1990, B) before fire suppression as of 1940.

paired t-test it was concluded that the Weibull fire cycle was not equal to the average age of the forest stands when the surface area was this small ($t_{.001,42} \approx 3.3$, $t = 6.6$).

The magnitude of variation around the mean of each age-class of the main drainage distributions (Figure 2.4) increased linearly over time from 1% to 252%. A variation less than 10% was found only for stands younger than 80 years. As for the discrete data (burn areas), the magnitude of variation was more than 50% for 82% of the age-classes, and peaked at 296% for the 180-190 age-class. Due to the great magnitude of variation already found within the main drainage basins, it was thought unnecessary to pursue this analysis for the 43 smaller watersheds.

While plotting the survivorship distributions for forest stands of the mountain parks, a couple of breaks (a change in trends) appeared in these distributions. These breaks were even more apparent when the distributions were plotted on semi-logarithmic paper (Figure 2.5). In Banff National Park, two breaks occurred around 1810 and 1650, while one break occurred around 1640 years in Mount Assiniboine Provincial Park.

Table 2.1 Chi-square goodness-of-fit test values for the watersheds (wtrd) of Banff National Park. The size of each watershed and the shape of its distribution is provided as well.

Wtrd no.	Name	Size (ha)	shape	X^2	n	$X^2_{.05,n-1}$	reject H_0
1	Alexandra	6503	4.02	2734.29	14	22.36	yes
2	Arctomys	3865	2.93	4.47	7	12.59	no
3	Baker	4523	2.36	315.08	12	19.68	yes
4	Bow-L	17158	3.65	52662.89	17	26.3	yes
5	Bow-M	44960	1.88	1238.22	30	42.56	yes
6	Bow-U	17068	2.04	34.20	18	27.59	yes
7	Brewster	8995	1.63	15.38	11	18.31	no
8	Bryant	8551	1.57	18.16	8	14.07	yes
9	Carrot	3026	10.22	9807.71	7	12.59	yes
10	Cascade	12667	1.91	28.53	14	22.36	yes
11	Castleguard	3200	3.93	72.03	9	15.51	yes
12	Clearwater-L	3319	3.74	52.15	10	16.92	yes
13	Clearwater-U	5584	5.09	27.31	11	18.31	yes
14	Corral	2023	35.43	5616.00	3	5.99	yes
15	Cuthead	2793	3.56	72367.44	8	14.07	yes
16	Divide	1956	2.39	0.49	4	7.82	no
17	Dolomite	2190	5.75	20.20	7	12.59	yes
18	Dormer	7622	1.57	35.10	16	25	yes
19	Flints	7351	0.81	64.71	18	27.59	yes
20	Forty-Mile	7361	6.17	2149368.52	9	15.51	yes
21	Healy	2463	2.11	7.97	10	16.92	no
22	Howse-L	10570	106.51	4.03	7	12.59	no
23	Howse-U	6524	3.27	6.19	6	11.07	no
24	Indianhead	943	5.11	7.61	9	15.51	no
25	Johnstone	5921	2.29	29.31	10	16.92	yes
26	Malloch	1180	1.43	31.19	7	12.59	yes
27	McConnell	2708	3.9	31.21	8	14.07	yes
28	Minnewanka	8019	2.08	82.73	16	25	yes
29	Mystaya	13006	2.66	33.30	15	23.68	yes
30	N-Sask.-L	12152	1.49	15.15	16	25	no
31	N-Sask.-U	7249	1.5	12.17	12	16.92	no
32	Panther	10574	2.55	55.70	18	27.59	yes
33	Peters	1058	1.43	1.17	7	12.59	no
34	Pipestone	13779	2	22.34	15	23.68	no
35	Red Deer-L	4959	1.81	9.29	11	18.31	no
36	Red Deer-U	9248	7.01	5138.52	16	25	yes
37	Redearth	9009	3.58	19.15	9	15.51	yes
38	Siffleur	2273	1.6	37.69	9	15.51	yes
39	Spray-L	17647	1.68	30.46	24	35.17	no
40	Spray-U	5558	11.6	10.99	5	9.49	yes
41	Stoney	3075	5.25	2066576.16	10	16.92	yes
42	Tyrrell	2516	2.8	1530196.42	6	11.07	yes
43	Wigmore	2280	2.93	6.70	8	14.07	no

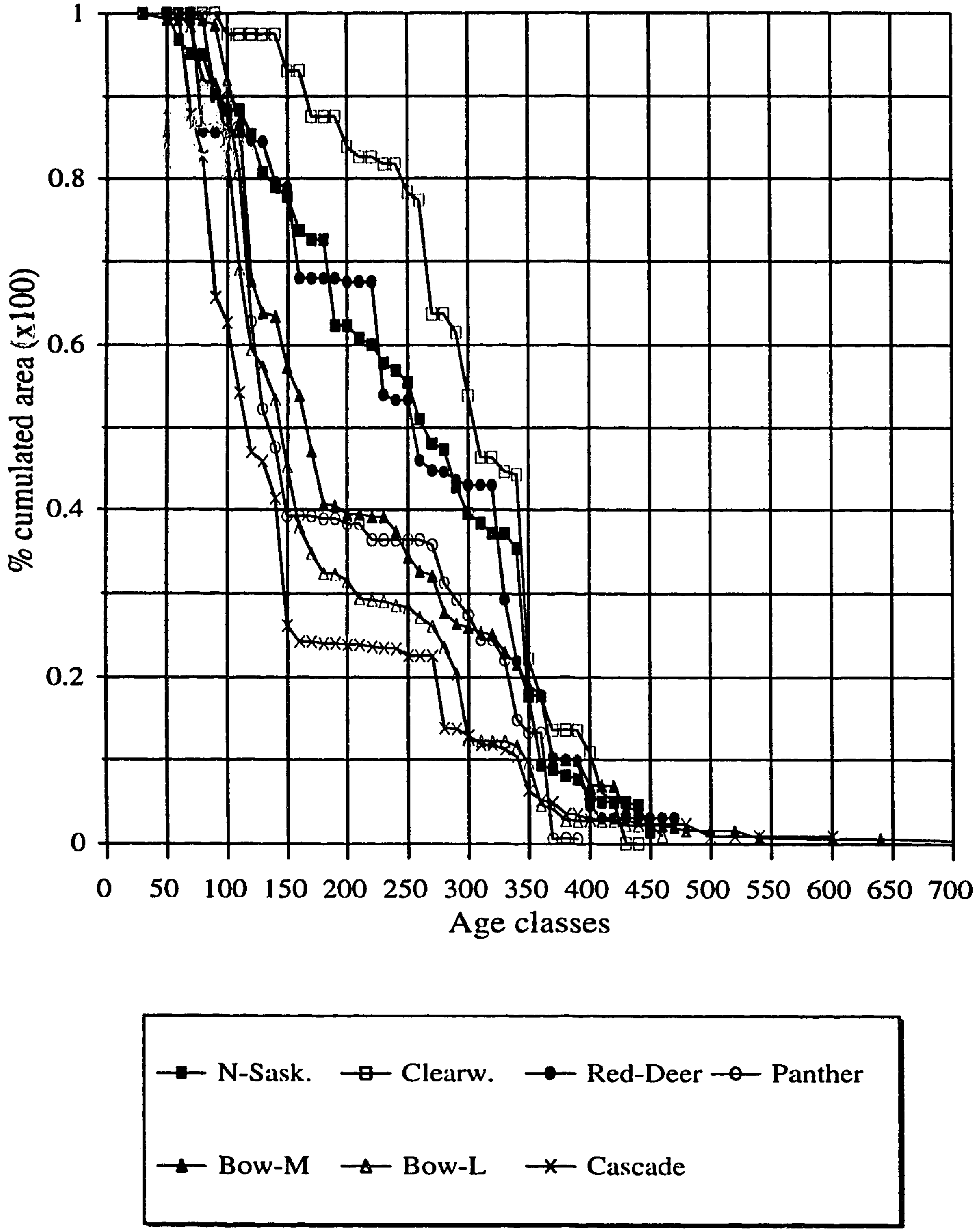

Figure 2.4 Survivorship distributions of the seven main drainages of Banff National Park.

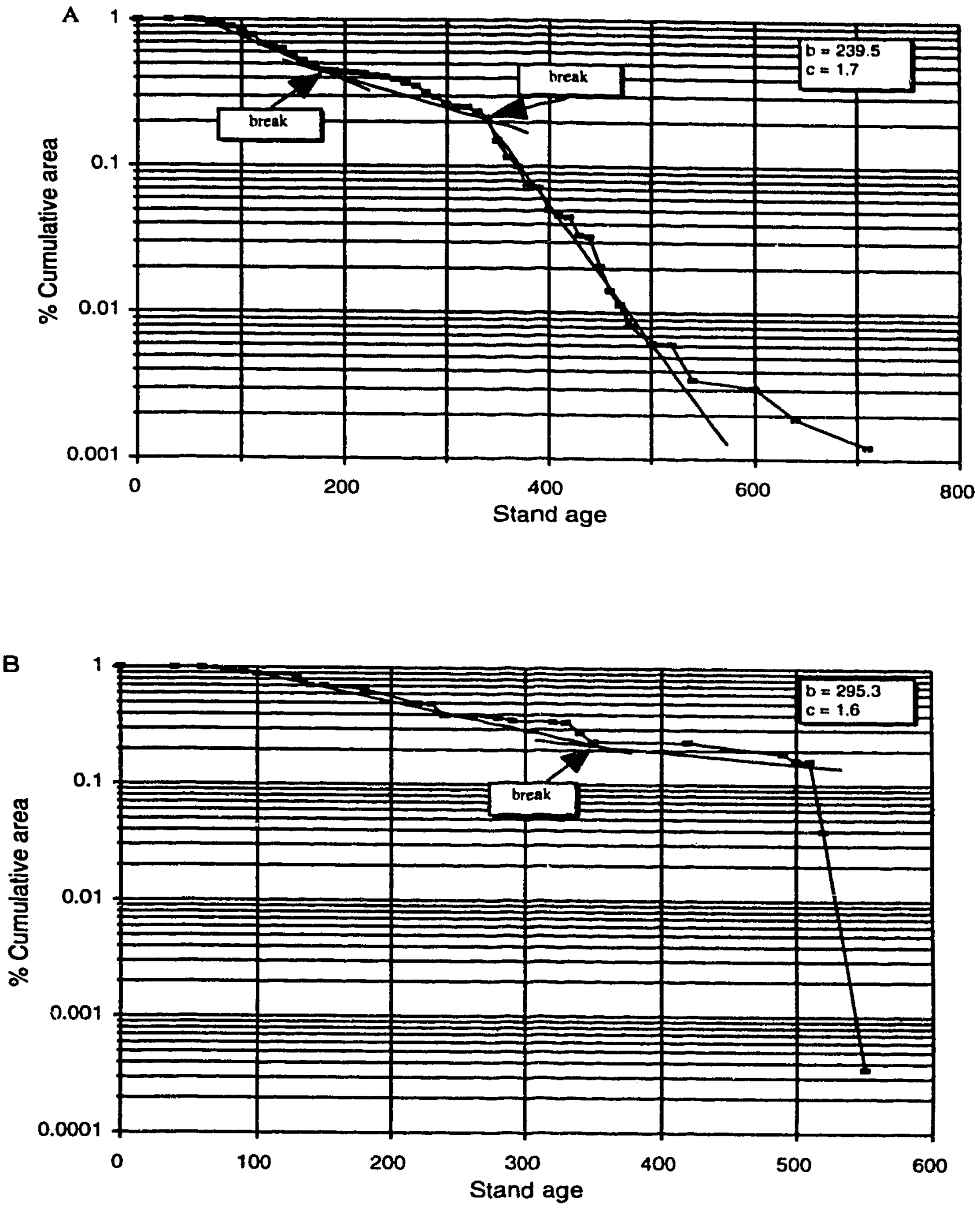

Figure 2.5 Survivorship distributions from similar areas commonly show unsynchronized changes in slope (break) when plotted on semi-logarithmic paper. A) Banff National Park, B) Mount Assiniboine Provincial Park.

2.5 Discussion

The study of the shape of the time-since-fire distribution and average age of the forest associated with each drainage basin of Banff National Park, contributed to our knowledge of the fire regime in this Park. Plotting of these survivorship distributions (Figure 2.4) suggests BNP is regulated by several fire regimes. It was found that the North-Saskatchewan river basin exhibited a similar mean age and distribution to that of the Red-Deer river basin. The Cascade and Lower Bow river basins also had a similar fire regime. Some drainages displayed similar survivorship distributions but only for certain periods of time. For example, the Panther drainage basin displays a survivorship pattern that was similar to that of the Lower Bow basin but only for the last 175 years. Before that, and up to 325 years ago, the survivorship pattern in the Panther basin actually looked more like the survivorship distribution found in the Middle Bow river basin. The Clearwater river basin has a distinctly peculiar fire regime, which seems to favour older aged forests, hence a longer fire cycle. All of these variations suggest far more complexity in survivorship patterns than has been suggested by previous studies of this area (Johnson *et. al.* 1990, Masters 1990, Johnson and Larsen 1991).

Most fire history studies in this ecosystem attributed a variation in slope to a change in the fire regime, which was caused by a change in a large scale climatic pattern, namely the Little Ice Age. However, unsynchronized changes in slope, occurring throughout each distribution of both Parks (Figure 2.5) and the main drainages (Figure 2.4), cannot support this premise. Perhaps, a break in slope occurring towards older age stands, a common feature shared by each survivorship distribution, should be perceived as a weakness in time-since-fire data. This is where fire information and evidence are too unreliable to interpret, due to limitations of the sampling method and to the small to extremely small surface area covered by these older age stands. Therefore, based on these results, perhaps the age-class distribution and fire regime of the area should not be interpreted beyond this break. Testing the statistical significance of a change in slope (a break) in the age-class distribution is further complicated by the fact that there is no replication in the data. These replications would provide the measure of variation required to test for significance.

The partitioning of BNP data also uncovered the fact that fire survivorship patterns vary greatly among sample areas. Hence, contrary to the suggestions in Johnson and Gutsell (1994), it is probably not wise to use survivorship patterns in small areas to predict what is happening in the larger landscape. This magnitude of variation in survivorship patterns suggests that fires do not select forested areas based on age. As an example, three regions under a similar fire regime experiencing fires in the year 1880, may yield to three different survivorship curves. Each survivorship distribution will behave differently because in one region the fire may burn over a young forest, while for another region it may replace an old forest, while in the third region, the burn can encompass an area of several different aged stands.

Additional factors which may contribute to this magnitude of variation between survivorship curves of different landscape units include the type, frequency, intensity and distribution of fires for each unit. It is well known that fire distribution and frequency in Banff National Park, especially for the last 100 years, depended mainly on the level of human use rather than lightning ignitions (White 1985). Those different fire regimes, which do not respect the criteria for homogeneity of the study area, interfered with the comparison of survivorship distributions of those different landscape units. Furthermore, in mountain regions, topographic components, such as valley orientation, elevation, aspect, valley width or abundance of fuelbreaks, are additional factors that contribute to the change in fire regime, and hence survivorship distributions should be expected to vary spatially. Therefore, the assumption that fire distribution was random throughout BNP and MAPP, and is likely to be the case in most mountain areas, does not seem valid. This statement is also supported by the shape of the survivorship distributions of Banff and Mount Assiniboine Parks, which do not plot as a negative exponential. The non-random fire distribution assumption perhaps explains why large forested areas in Banff National Park have remained unburned for several centuries. This suggests that the fire cycle varies spatially over the landscape; a hypothesis which should be tested further.

The fact that fires are not random in the mountains and that most fire history studies in this area have unreliable fire history data (Agee *et. al.* 1990, Masters 1990, Johnson and Larsen 1991, Rogeau and Gilbride 1994), means that the average age of the forest and the fire cycle have been falsely represented. This is because older age stands, usually older than 300 years, are often aged based on the oldest tree sampled and not necessarily the date of the fire event that established the stand. It is impossible to know from current methods of fire history analysis, if those stands have been self-regenerating for decades, or even centuries in cases where the forest is not located in fire prone areas. Thus, the average age of the forest and the fire cycle are expected to be greater to an unknown extent. Therefore, it can be assumed, based on time-since-fire data before fire suppression, that the fire cycle in Banff National Park is **at least** as long as 170 years, and that the fire cycle in Mount Assiniboine Provincial Park is **at least** as long as 220 years. However, because the fire cycle is expected to change over the landscape, due to the non-random fire starts, the fire cycle can possibly be as long as 300 years in high subalpine areas and perhaps as short as 50 years in montane zones. Overall, the fire cycle provided by the Weibull model is simply an average fire cycle for the entire area without regard to spatial differences.

Failing to respect the criteria with regard to the minimal extent of the area significantly influenced the ability of the model to accurately capture the survivorship distribution and the fire cycle. Small valleys that succumbed to large fires had a limited assortment of stand ages, which contributed to the poor fit of the model to those time-since-fire distributions. Therefore, any kind of spatial partitioning of the landscape must be done wisely to ensure that the size of the study area remains much greater than the largest burn area in order to preserve a broad diversity of age-classes. Otherwise, the fire regime and fire cycle may be falsely represented and inappropriate forest and fire management decisions may result.

Lastly, it is recommended that care be exercised when fire history data are analysed with the Weibull or negative exponential model. Fire history data, used as survivorship data, may be sending the wrong message if the distribution is misinterpreted. Usually the analysis of lifetime data are accomplished by starting with a population of a known size and by keeping track of the number of individuals that die. This information is used to produce a death rate, the inverse of which is the survival rate. For the historical analysis of fires, one must use surface areas of forest stands that ***survived*** fire since the original size of the stand population "at birth" is unknown due to the overlapping nature of fires. To help illustrate the fact that the fire history models may send the wrong message, Figure 2.6 provides an example of time-since-fire data plotted as a mortality curve as well as a survivorship curve. A mortality curve is in fact a mirror (reverse) image of a survivorship curve (Johnson and Gutsell 1994). Time-since-fire data, which are composed of a population of survivors to catastrophic fire events, reflect a false image of the reality when plotted as a mortality curve. The survivorship curve in Figure 2.6, suggests that after 200 years, 25% of the forest survived fires and that after 350 years, only 8% of the forest remained unburned. As for the mortality distribution, it tells us that after 200 years, 75% of the forest has burned while after 350 years, 92% has burned. Because true fire sizes are lost over time due to subsequent fires overlapping older burn areas, the percent of burned forest after 200 years could in reality be much greater than 75%. The mortality distribution must be interpreted as such: 75% of the forest cover is younger than 200 years. The mortality distribution does not provide the percent of forest that has burned after a certain period of time, nor does it indicate the age of the stands at the time of burning.

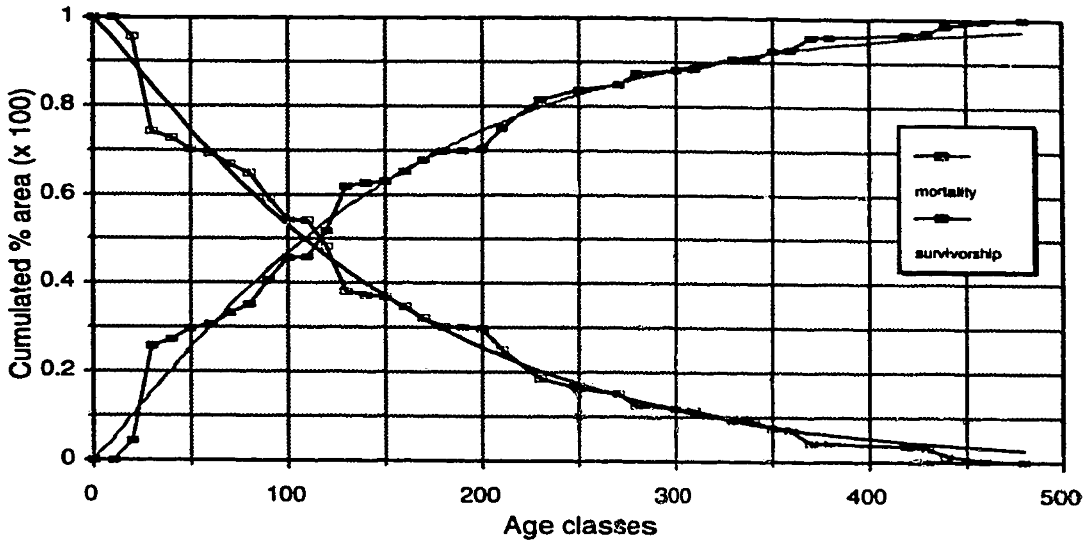

Figure 2.6 Survivorship distribution and its mirror image representing the mortality distribution.

2.6 Conclusion

The Weibull function which is commonly used to model time-since-fire data, could not accurately predict the fire cycle for small areas with a restricted number of age-classes, but also for mountain areas in general. In the mountains, the main assumption of homogeneity of the fire regime is not respected and fires are not randomly distributed. Thus, the fire regime and fire cycle vary spatially. Temporal variations must also be expected due to natural fluctuations in fire size and frequency. Poor accuracy in dating older age stands reduces to some extent the length of the fire cycle over the entire landscape.

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CHAPTER III

Interpreting fire history data through simulated fire regimes

3.1 Introduction

Determination of an accurate fire cycle is a key component of modern forest management techniques, and this factor has been used extensively by park and forest service managers. This term represents the time required to burn an area equal in size to the study area, assuming the fact that some areas may burn more than once and others not at all (Van Wagner 1978, Romme 1981). The inverse of the fire cycle also provides, in theory, the annual average percent of area that historically burned in a management unit (Johnson and Van Wagner 1985). In a prescribed burning program, this measure is used to estimate the average amount of land that should be burned annually in order to sustain the natural fire cycle and hence, the diversity common to the natural forest age structure for the area.

The historical role of fire and determination of a fire cycle have traditionally been studied using the Weibull model and its variant, the negative exponential (Johnson and Van Wagner 1985, Johnson *et. al.* 1990, Masters 1990, Johnson and Gutsell 1994). These models are considered the most appropriate for analysing the "survivorship" of forest stands relative to stand replacing disturbances such as fire (Johnson 1979). A complete description of these models and their equations have been adequately addressed by Lawless (1982), Johnson (1979), Van Wagner (1978), Johnson and Van Wagner (1985) or Johnson and Gutsell (1994).

In summary, the Weibull function models survivorship distributions, also called time-since-fire distributions, in the cumulative form. Such distributions come from time-since-fire maps where stands have been delineated by age since the last fire. Surface areas of stands of similar age-classes are simply computed and plotted cumulatively by using the percent of area occupied by each age-class in the distribution. The Weibull time-since-fire distribution model has been defined by Johnson and Gutsell (1994) as:

$$A(t) = \exp(-(t/b)^c) \qquad \textbf{[3.1]}$$

The scale parameter b is the expected recurrence time of fire (years), t is the age of forest stands and c is a dimensionless shape parameter. Depending on the application, c will vary but in many situations as shown in Figure 3.1, the shape value (c) will range between 1 and 3 (Lawless 1982). The shape parameter of the Weibull model accounts, in theory, for the change in risk of burning. A distribution with $c > 1$ portrays a risk of burning that increases over time, or with the age of the forest, while $c < 1$ represents a decrease in the risk of burning with age. When $c = 1$, the distribution is a negative exponential. Thus, the negative exponential is simply a special case of the Weibull model (Figure 3.1). In this case, Van Wagner (1978) and Johnson and Gutsell (1994) suggest that the risk of burning is constant over time, which assumes that fire occurrence is a random event.

The negative exponential distribution is sometimes preferred when modelling survivorship patterns based on cumulated age-class distribution data, because it involves the use of only one parameter (scale) and data can be plotted as a descending straight line on semi-logarithmic paper (Van Wagner 1978). This distribution is extremely popular because of the relative ease in calculating the fire cycle, which simply consists of a linear regression

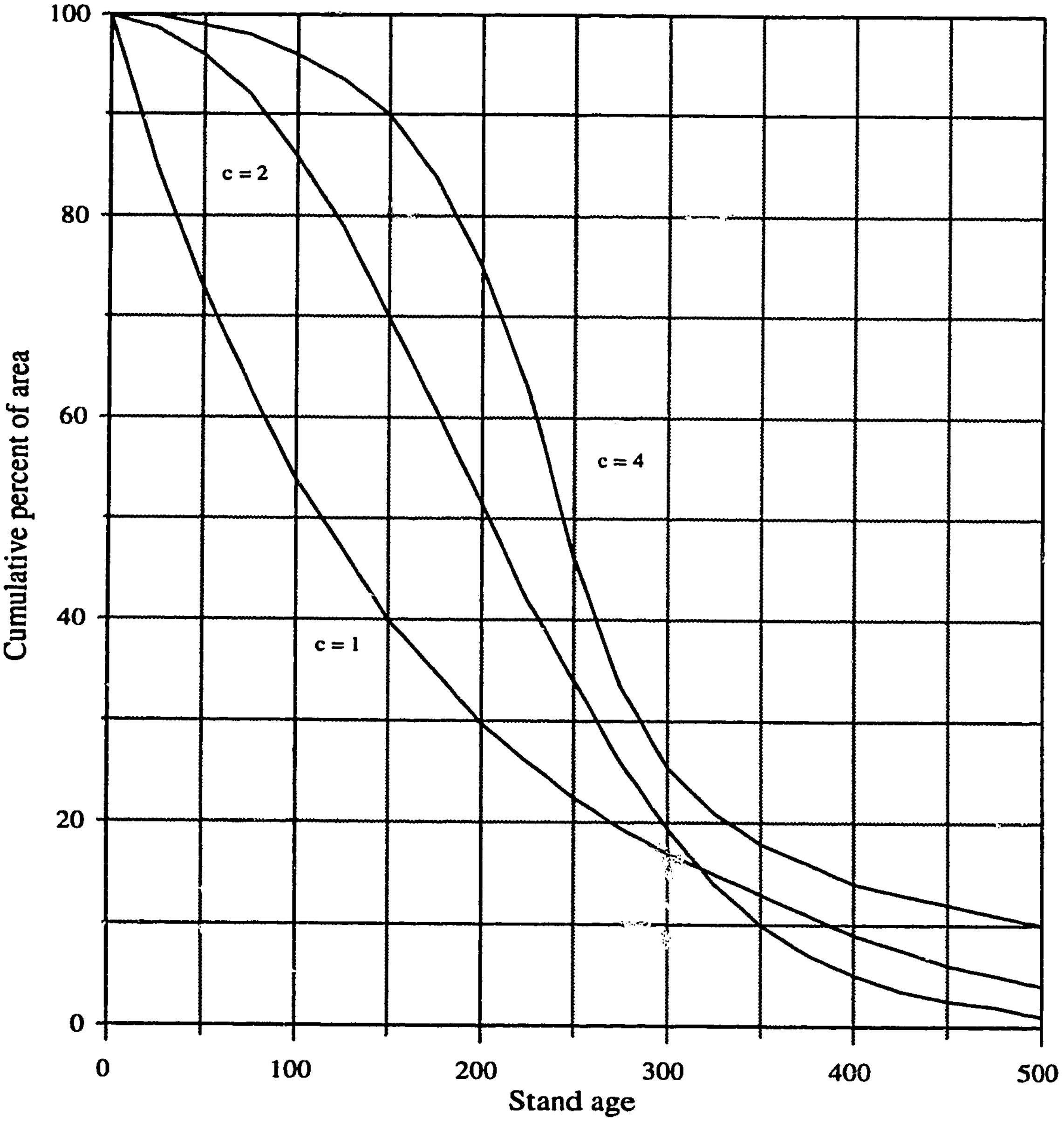

Figure 3.1 The Weibull survivorship function. Distributions common to time-since-fire data have a shape value (c) that vary from 1 to 4 in general. A distribution with a shape of 1 plots as a negative exponential.

analysis and the calculation of the inverse of the slope of the line of best fit. However, for this model to work best, the risk of burning must be constant over time and space, and it must be assumed that forest age does not influence the probability of burning (Johnson and Larsen 1991). Previous fire history studies have shown that data from the Canadian Rockies produce survivorship curves that are relatively well fitted by a negative exponential distribution (Johnson *et. al.* 1990, Masters 1990, Johnson and Larsen 1991).

It was demonstrated by Van Wagner (1978), through fire modelling, that the negative exponential model has two important properties: (1) the fire cycle (the inverse of the slope of the line of best fit) equals the mean age of the forest, and (2) 63.2% of all stands are younger than the mean age. Hence, he concluded the probability of a stand surviving throughout an entire fire cycle to be 36.8%. His findings seem to support an assumption that fire occurrence is random across the area sampled and that some landscape units burn more than once while others not at all. Because the parameter "*b*" of the Weibull fire cycle equation (Equation 3.2, Methods) is multiplied by a term (gamma function of 1/c + 1) that ranges normally between 0.9 and 1.1 for distributions with a shape value (c)ranging between 0.8 and 4, it can be assumed that the fire cycle of the Weibull model portrays something close to the mean forest age as well. However, for the fire history models to adequately predict the fire cycle or the mean forest age, several assumptions and criteria must be respected.

Assumptions and criteria

Johnson and Van Wagner (1985) emphasized the importance of restricting the use of these models to only homogeneous areas. Homogeneity is important relative to two important criteria which greatly affect the stability of the data sets: (1) the area of interest must be under a similar fire regime, and (2) the fire regime must be constant, on average, over the range of years covered by the fire history data. Another important criteria specifies the minimum size of the study area, which is based on the largest fire likely to be experienced within the area per year. As a rule of thumb, the largest possible fire occurring, or the maximum area burned in one fire year, should not exceed one third of the total surface of the study area (Johnson and Gutsell 1994). Additionally, the fire cycle should also be short in comparison to the time period of the fire history study. Johnson and Van Wagner (1985) suggest studies that span time periods longer than 400 years may have been affected by climatic changes, which are likely to occur over such a long time period. They further suggest that a change in climate might be reflected by a change of slope in the age-class distribution of the sampled population.

Several problems are associated with the use of those models. First, they have never been validated due to the overlapping nature of fires. It is well known that with repeated burning, evidence or boundaries of previous burn areas may be greatly reduced or lost. For example, an 1820 fire-originated stand, mapped as 500 ha in 1995, originally could have been as big as several thousands hectares but the boundaries of this original area have been masked by subsequent fires. Hence, the actual fire cycle of an area is unknown, and it is impossible to reconstruct them by simply using time-since-fire data. Second, those models apply to spatially independent units of equal size (Van Wagner 1978), which is not a realistic assumption for burning patches of forest. Fire size and frequency are highly variable over the years (Murphy 1985) due to spatial and temporal dependencies of forested landscape units (Boychuck *et. al.* 1995). Third, the effect of "size of study area" in relation to the fire size distribution is not well understood, especially in the boreal forest where fires can become extremely large. As a study area increases in size, the probability of getting a rare devastating fire event increases as well. Hence, the question is "How large must the study area be to meet the eligibility size criteria for using the Weibull model?" In addition, will a failure to respect any of the assumptions and criteria impact on the ability of the models to estimate the fire cycle for the study area.

Most previous fire regime studies have been based on one survivorship curve for a sample area (Johnson *et. al.* 1990, Masters 1990, Johnson and Larsen 1991), which really amounts to a sample size of one. This approach may significantly limit the reliability of the method. Hence, "Is it legitimate to assume that the present-day age-class distribution was similar to the ones found 75, 150 or 300 years ago?" Also, "What is the magnitude in survivorship patterns that one should expect to find?" These problems must be investigated to determine the suitability of using the present-day survivorship distribution as a means of understanding the fire regime for an area.

The purpose of this research was to propose a new approach to understanding and predicting the role of fire in specific ecosystems. Through simulated fire survivorship (time-since-fire) distributions, the accuracy of the Weibull model was tested, and the magnitude of variation in survivorship patterns was evaluated. Specifically, a fire simulation program was designed to replicate time-since-fire maps and age-class distributions using real world data, and to keep track of the number and original size of fires before they were over burned by subsequent fires. This last feature was essential for calculating the real fire cycle of the simulations for the target area. As a result, it was possible to compare the real fire cycle to the estimated fire cycle calculated from the Weibull model. The ability of the Weibull model to explain fire cycle was tested for three types of fire regime, which were characterized by various fire sizes and frequencies.

3.2 Methods

A fire regime simulation program was written to produce time-since-fire maps and survivorship curves. The rules governing the program were: (1) the spatial fire distribution for the fire regimes was assumed to be random, and (2) the burnt forest was presumed to be available for burning within the following decade. This last assumption was adopted so that the risk of burning would be constant over time rather than increasing with the age of the forest. It has been suggested that the probability of burning increases with age for some areas of the Boreal forest (Rowe *et. al.* 1975, Johnson 1979), however there is insufficient data to substantiate a constant increase in frequency of burning in older aged forests.

The fire regime simulation program created maps by 10-year period, where: (1) fire frequency was randomly[1] selected out of a range of possible frequencies, which varied based on the fire regime being modelled, (2) fire size was randomly picked out of an array of 100 possible fire sizes, which characterized the fire regime being modelled, and (3) fires were

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[1] The programming language used successive pseudo-random numbers in the range from 0 to (2^{15}) -1.

"seeded" over a 300 000 ha square area by positioning the centroid of the fires on randomly selected X,Y coordinates. The simulation run was set to 500 years, therefore this procedure was repeated 50 times to create 50 maps. Afterward, these maps were overlayed in such a way that the most recent 10-year period took precedence over the older ones. The end result of the overlaying process was a time-since-fire map, which displayed a mosaic of different stand ages that was produced by overlapping fires. Such method of analysis and display clearly shows, as represented in Figure 3.2, how a time-since-fire map can mask previous age-class distributions and how the true size of previous burn areas can be lost over time because of overlapping fire boundaries. Contrary to real time-since-fire data, where true fire sizes of older fires are lost, the fire simulation program kept track of the fire size and number of fires per decade. This feature permitted tabulation of the burn area for each 10-year period until the amount of burn area equaled 300 000 ha, which is the size of the simulated study area. The number of years it took to burn an area equal to the study area is then the *true fire cycle* of the simulated fire regime.

Algorithm of the fire regime simulator

1. Select size of the study area
2. Create discrete array of 100 fire sizes (fire size distribution)
3. Select duration of simulation in years (L_s)
4. Select length of age-class in years (L_a)
5. Randomly select fire frequency from a range of number of fires (n) to burn per age-class
6. Begin seeding of fires at time = Ls
    a. Randomly select x and y coordinates within the study area
    b. Place centroid of fire at (x,y)
    c. Record actual fire size, and area falling outside study region
    d. Repeat steps a. to c. for n fires within the age-class
    e. Increment simulation time by L_a years

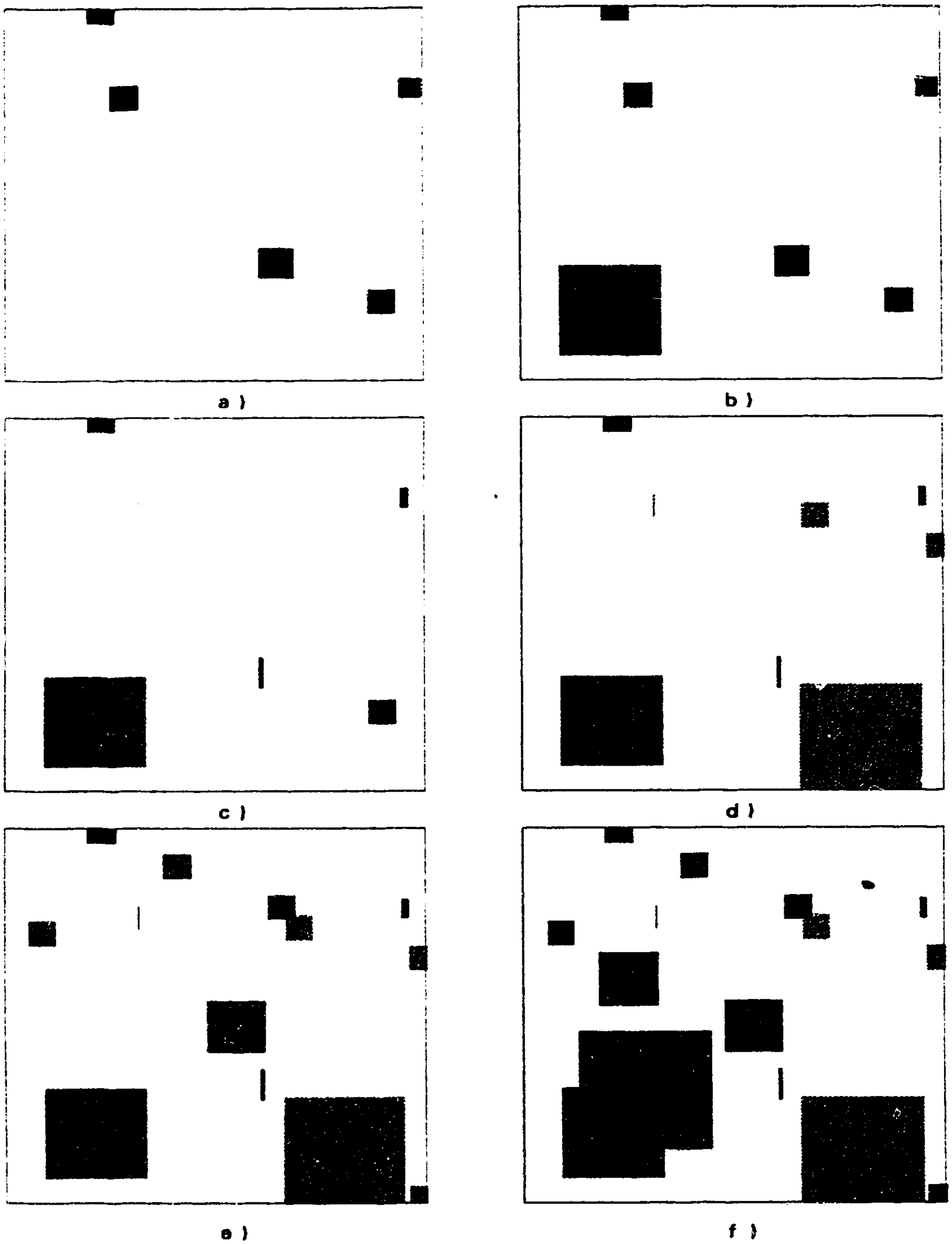

Figure 3.2 Simulated fires (squares) demonstrate the overlapping nature of fires over time: a) after 10 yrs, b) after 20 yrs, c) after 30 yrs, d) after 40 yrs, e) after 50 yrs, and f) after 60 yrs. This example represents only a small window (60 years) in the time span of time-since-fire data which may extend beyond 500 years. From this figure, it is clear that burn areas are greatly reduced in size over time and may eventually disappear.

f. Repeat steps a. to e. for L_s/L_a iterations
7. Record final time-since-fire map area occupied by each age-class

Three scenarios, which simulate three distinct fire regimes, were created by simply using various combinations of fire sizes and fire frequencies. If the fire size distribution, fire frequency and fire locations are assumed to be random, the average fire cycle for an area can be estimated by using basic fire statistics such as the average fire size and average fire frequency for the area. The fire cycle for each scenario was therefore estimated in two simple steps. First, the average number of fires required to burn the whole study area was calculated by dividing the size of the study area by the average fire size, and secondly, the average number of fires, as calculated in step one, was divided by the average fire frequency. The later calculation gave an estimate of the average fire cycle for the fire regime being modelled.

Scenario 1 simulates a fire regime encompassing large fires, but of low frequency so that about 3 fire cycles of about 147 years could be obtained for a period of 500 years under a fire suppression regime. This is thought to resemble the situation common to the Boreal forest of northern Alberta. The number of ignitions in this case, ranged from 1 to 5 fires per decade. Fire sizes were estimated based on results of published data for the Boreal forest by Delisle and Hall (1987). In **Scenario 2**, which was named the "Mountain fire regime under partial fire suppression", the fire regime was characterized by small size fires, in comparison to the study area, and by a low fire frequency of 1 to 5 fires per decade. This combination of parameters will produce a fire cycle of about 500 years, which correspond to the length of the simulation time. Because fire size statistics came from Banff National

Park, Alberta (Rogeau and Gilbride 1994), which is located in the Southern Canadian Rockies, this scenario is thought to closely represent the fire regime of that Park for the period of 1910 to 1940. **Scenario 3** represents a "Mountain fire regime without fire suppression". Again fire size statistics were from the Banff National Park data set. However, in this case fire frequency was much greater. It ranged between 1 to 15 fires per decade, which is thought to closely represent the actual fire regime of Banff National Park before the impact of fire suppression activities. Under these conditions, the fire regime yields about 3 fire cycles of 173 years for each 500-year period.

Simulations were run for a period of 500 years on a square hypothetical study area of 300 000 ha (3 000 km^2), which by design was homogeneous in all aspects important to fire occurrence, growth, behavior and effects. It must be noted that fires were allowed to grow beyond boundaries of the study area. The 500-year period was chosen to mimic real time-since-fire data. Even though stands as old as 700 years have been found in the boreal and mountain forests of Alberta, areas of very old forest are small and uncommon, perhaps due to the life expectancy of trees native to these regions. The size of the study area was picked to equal the amount of burnable forested land in Banff National Park. As Banff represents the largest real time-since-fire database available in the mountain regions, keeping a similar size for the time-since-fire simulations could allow for comparisons between real and simulated data.

Fire size classes that were used as inputs by the program to simulate the fire regimes are presented in Table 3.1. Fire size statistics for the fire regime modeling large size fires of the Boreal forest (Scenario 1) were obtained from forest fire history maps of Alberta for the years 1931 to 1983 (Delisle and Hall 1987), while size of burn areas for the mountain fire regime were obtained from the time-since-fire map of Banff National Park (Rogeau and Gilbride 1994). To determine the exact size of previous fires in the Park, only those areas that had not been overlapped by younger fires were chosen. As shown in Table 3.1, the probability for the simulation program to choose a fire size within a certain size class, equals the percent of fires within that class. Fire sizes within each size class varied at regular intervals according to the percent of fires within that class. As an example, data published by Delisle and Hall (1987) suggests that in the Boreal forest, 3% of the fires fall within the size class 25,000 - 50,000 ha. Hence, for the simulations of burn areas within that class, the computer program randomly picks one of three fire sizes (30,000, 40,000, 50,000) 3% of the time. However, it is understood that in reality, any fire sizes between 25,001 and less than 50,000 ha could be encountered.

The actual size of the fires impacts on the accuracy of the results obtained. In reality, small size fires are often undetected due to different resolutions in the mapping and survey techniques used. For the simulations, the smallest burnable unit thought to be significant enough to impact the fire cycle was set to be 200 ha, which represents 0.07% of the simulated study area. The largest possible fire occurring in the simulations for the Boreal forest (Scenario 1) was 100,000 ha, although, in reality, it is quite common to experience fires much greater in size. The 100,000 ha fire size was selected to respect the model's criterion of "the study area should be at least three times bigger than the largest fire" (Johnson and Gutsell 1994). It should be stressed that the fire size limitation for the

Table 3.1 Array of fire sizes used for fire simulations of the Boreal and Mountain fire regime.

BOREAL			MOUNTAIN		
Fire size classes	% of fires	Array of fire sizes	Fire size classes	% of fires	Array of fire sizes
200 - 1 500 ha	53	200, 225, 250, 275, 300, 325, 350,..., 1 425, 1 450, 1 475, 1 500	200 - 500 ha	16	200, 220, 240, 260, 280, 300, 320,..., 460, 480, 500
1 500 - 11 000 ha	36	1 750, 2 000, 2 250, 2 500, 2 750,..., 10 250, 10 500, 10 750, 11 000	500 - 1 000 ha	25	520, 540, 560, 580, 600, 620, ..., 960, 980, 1 000
11 000 - 25 000 ha	6	12 500, 15 000, 17 500, 20 000, 22 500, 25 000	1 000 - 2 000 ha	20	1 050, 1 100, 1 150, 1 200, ..., 1 900, 1 950, 2 000
25 000 - 50 000 ha	3	30 000, 40 000, 50 000	2 000 - 3 000 ha	13	2 075, 2 150, 2 225, ..., 2 825, 2 900, 2 975
50 000 - 75 000 ha	1	75 000	3 000 - 4 000 ha	13	3 075, 3 150, 3 225, ..., 3 825, 3 900, 3 975
75 000 - 100 000 ha	1	100 000	4 000 - 5 000 ha	7	4 000, 4150, 4 300, 4 450, 4 600, 4 750, 4 900
			5 000 - 10 000 ha	3	7 000, 8 000, 9 000
			10 000 - 20 000 ha	3	12 000, 15 000, 18 000

simulations pertaining to the boreal forest will yield a longer fire cycle than what would be expected in reality. Murphy (1985) calculated a fire cycle for the Northern forest of Alberta that increased from 38 years in 1909 to 90 years in 1969. For the Mountain fire regime, the largest fire (18,000) was based on the largest "known" fire ever experienced by Banff National Park in the last two centuries. Due to valley orientation and numerous fuelbreaks in the Rocky Mountains, fires peculiar to the Mountain fire regime tend to be much smaller in size than those in the Boreal forest area of Alberta.

For unknown reasons, there are fewer fires in the smallest size category 200 to 500 ha (n = 16) in Banff National Park (mountain fire regime) than in the fire size class 500 to 2,000 ha, which had a n = 25. In general, for problems of this nature, the probability for small disturbing events are usually much higher than large catastrophic events, and the frequency of those events should decline exponentially according to their magnitude (Bak and Chen 1991). Perhaps burning conditions in Banff National Park favor larger size fires, thus it either burns "hot" or not at all, or more likely it is because it is difficult to find small size fires especially in older forest stands.

The simulated fire regimes were replicated several times. Fifty simulations were done for Scenario 1 and 2, while 25 simulations were produced for Scenario 3. For each simulated time-since-fire map produced, 125 in total, the surface area for every stand age was obtained. The percent of area for all stand ages was calculated and cumulated in such a way that at time zero, 100 % of the area was covered (Figure 3.1). Parameters of the Weibull model were estimated using the SAS statistical package (SAS Institute Inc. 1985).

The goodness-of-fit of each simulated survivorship distribution was calculated using the Pearson's Chi-square goodness-of-fit statistic (Ott 1993) at a significance level of .05. Although other goodness-of-fit tests have been suggested by different authors, this test was chosen because it was more appropriate for this experiment. Johnson and Larsen (1991) have proposed the use of the "WE test", which is designed to evaluate the goodness-of-fit to a negative exponential distribution. The inconvenience of this test was that the percentage points for hypothesis testing are only available for a population (n) < 35 (Hahn and Shapiro 1967). For this research, simulated distributions comprised a population of age-classes ranging from 35 to 51, and several distributions took the form of a Weibull distribution rather than the negative exponential. The popular Kolmogorov-Smirnov test was also considered as a possible test but its precision is lessened when the sample size is > 20 (Conover 1971).

The *Weibull fire cycle*, as defined by Johnson and Gutsell (1994):

$$\textit{Weibull fire cycle} = b\Gamma[\frac{1}{c} + 1] \qquad [3.2]$$

was calculated for each time-since-fire simulation by using the estimated b and c parameters from the model (Equation 3.1). The *true fire cycles* were computed by adding the area burned until it equaled the total size of the theoretical study area (i.e. 300 000 ha). It should be noted that fire sizes used in all calculations did not include portions of fires that burned beyond the limits of the study area. The *average age of the forest* was calculated by multiplying each stand age by its percentage of area and by summing those weighted stand ages.

The magnitude of variation expected from a survivorship distribution was estimated by using the first 15 simulated distributions created for each scenario. Fifteen simulations were considered sufficient and statistically representative to calculate the standard deviation around the mean of the 50 age-classes of the survivorship distribution. This procedure was performed on discrete data (surface area) and for the cumulated distribution (cumulative % of area). It was decided that a present-day survivorship distribution, obtained from real time-since-fire data, would be reliable if the standard deviation remained within 10 percent of the mean value, and that, for 80 percent of the age-classes of the simulated survivorship distributions. This approach was considered to be more informative than comparing the shape parameter of the simulated distributions, because it provided a means of appraising the survivorship fluctuation over the years. This information should help in identifying those sections of the distribution that are less reliable in estimating the past fire regime.

The ability of the Weibull function to estimate the fire cycle was tested with a paired *t*-test, at a significance level of .05 (Ott 1993). Paired values were compared between the *Weibull fire cycle* and the *average age of the forest*, and between the *Weibull fire cycle* and the *true fire cycle*. A coefficient of correlation (r^2) was also computed between all the paired variables to obtain a measure of the strength of their relationship. Those tests were performed for time-since-fire distributions of the three scenarios. It was felt that the Weibull model should be able to predict the *true fire cycle* and the *average age of the forest* within 25 years, and that, 80% of the time if it was to be used for management purposes. Therefore, the time difference between the different variables assessed, i.e. *Weibull fire cycle - true fire cycle, Weibull fire cycle - average age of the forest*, was calculated as well.

3.3 Results

Examples of a time-since-fire map for scenarios 1,2 and 3 are represented in Figure 3.3. This figure demonstrates quite clearly, by the size of the fires, the relative differences in fire regime among the three scenarios tested. It should be noted, however, that the random nature of the simulated fire distribution caused several cells, which represent land units, to remain unburned even after a period of 500 years. On average, seven percent (21 000 ha) of the area tested in Scenario 1 did not burn, while on average, thirty-four percent (102 000 ha) and six percent (18 000 ha) of the area in Scenario 2 and 3, respectively, escaped burning. The high number of unburned cells may be attributed to the limitations of the fire simulation program but due to the frequency of occurrence, it is most likely due to the type of fire regime modelled. Fire regimes that yield a long fire cycle, such as Scenario 2 (Mountain environment under fire suppression) will likely have a lot of unburned areas, unless fire simulations are run for a longer time period. In addition, the assumption of randomly distributed fires, where stand age is independent of burning conditions, is perhaps not that realistic. Because fires were allowed to burn areas that had been burned in the previous decade, it was common to observe, during the simulation process, fires burning right over top of a recent burn. In reality, such young stands would likely not support a stand replacing fire, and fire would probably burn in an older stand which can support crowning. Random fire distribution is an outcome that should be evaluated further.

All of the mountain simulations, with and without fire suppression, were well fitted by the Weibull model ($\mathbf{X}^2_{.05,n-1}$), but 18% of the Boreal simulations (Scenario 1) rejected the fit. Table 3.2 presents the range, mean and standard error of the shape values (*c*) calculated

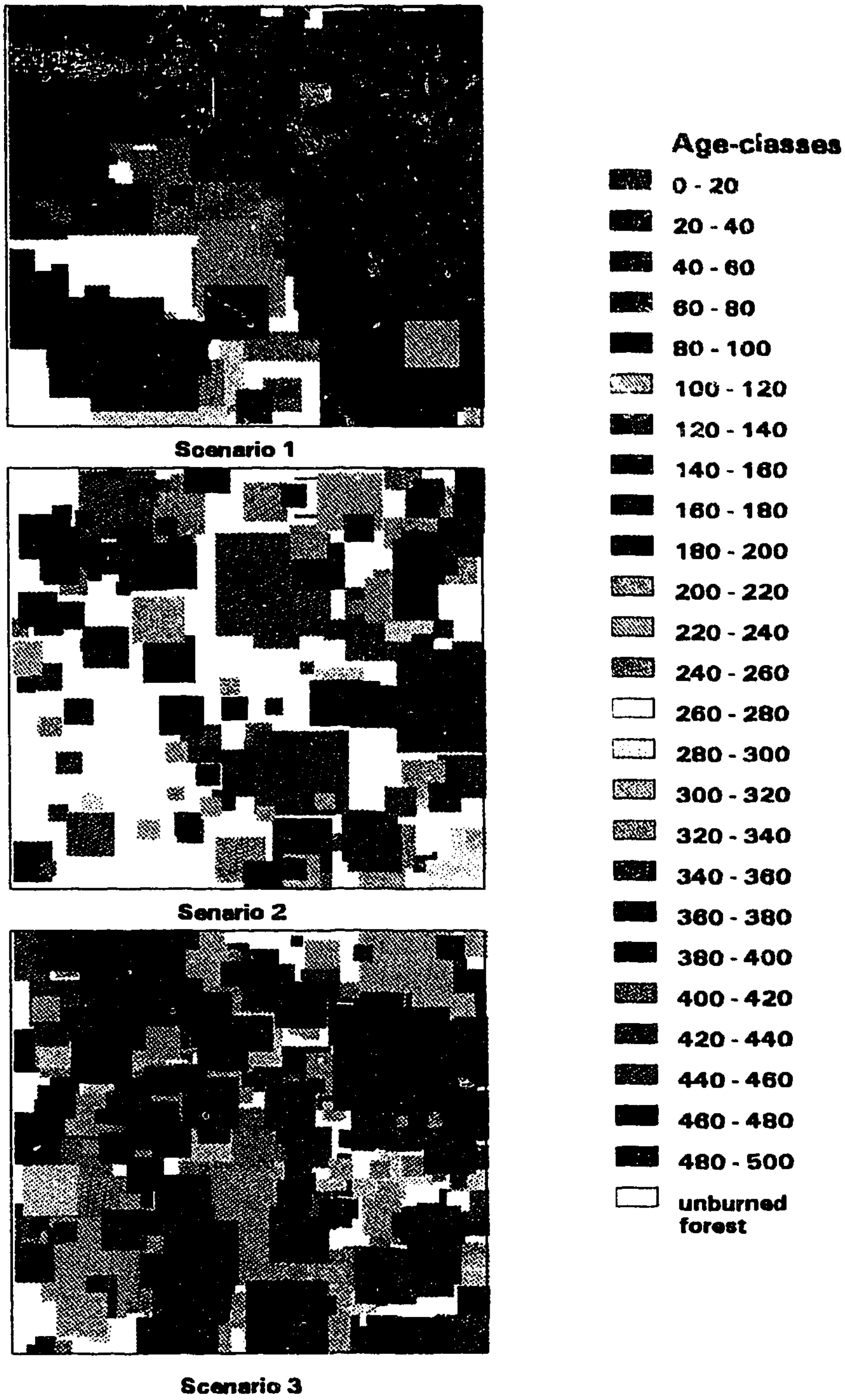

Figure 3.3 Example of a simulated time-since-fire map for Scenario 1: Boreal fire regime under fire suppression, Scenario 2: Mountain fire regime under partial fire suppression, and Scenario 3: Mountain fire regime without fire suppression.

for the survivorship distributions of the three case scenarios. Results of the Goodness-of-fit test, as well as the shape of the simulated distributions, are presented in Appendix C. Two representative examples of simulated survivorship distributions for each Scenario are presented as well in Figures 3.4, 3.5 and 3.6.

Table 3.2 Range, mean and standard error of shape values (*c*) for simulated time-since-fire distributions of the three case scenarios.

	Range	Mean	Std error
Scenario 1	0.6 - 2	1.1	0.3
Scenario 2	0.8 - 1.6	1.1	0.2
Scenario 3	0.8 - 1.3	1.1	0.1

Calculations for the estimates of the magnitude of variation for survivorship patterns are provided in Appendix D. Table 3.3 presents the age-class with the minimum and maximum variation in survivorship patterns calculated for the discrete data (burn areas), the magnitude of variation for the cumulated percent area, which always increased linearly from the younger age-class to the oldest one, and the portion of the stand age distribution that was the most reliable, i.e. with less than 10% variation. The magnitude of variation of the first 15 simulated survivorship distributions for each of the three Scenarios are presented in Figures 3.7, 3.8 and 3.9. These figures clearly show the increased variation in survivorship patterns as stands become older.

Results of the ability of the Weibull model to estimate the *true fire cycle* or the *average age of the forest* are summarized in Table 3.4. With the exception of the test "Weibull fire cycle / true fire cycle" for Scenario 2, the paired t-test rejected the equality of

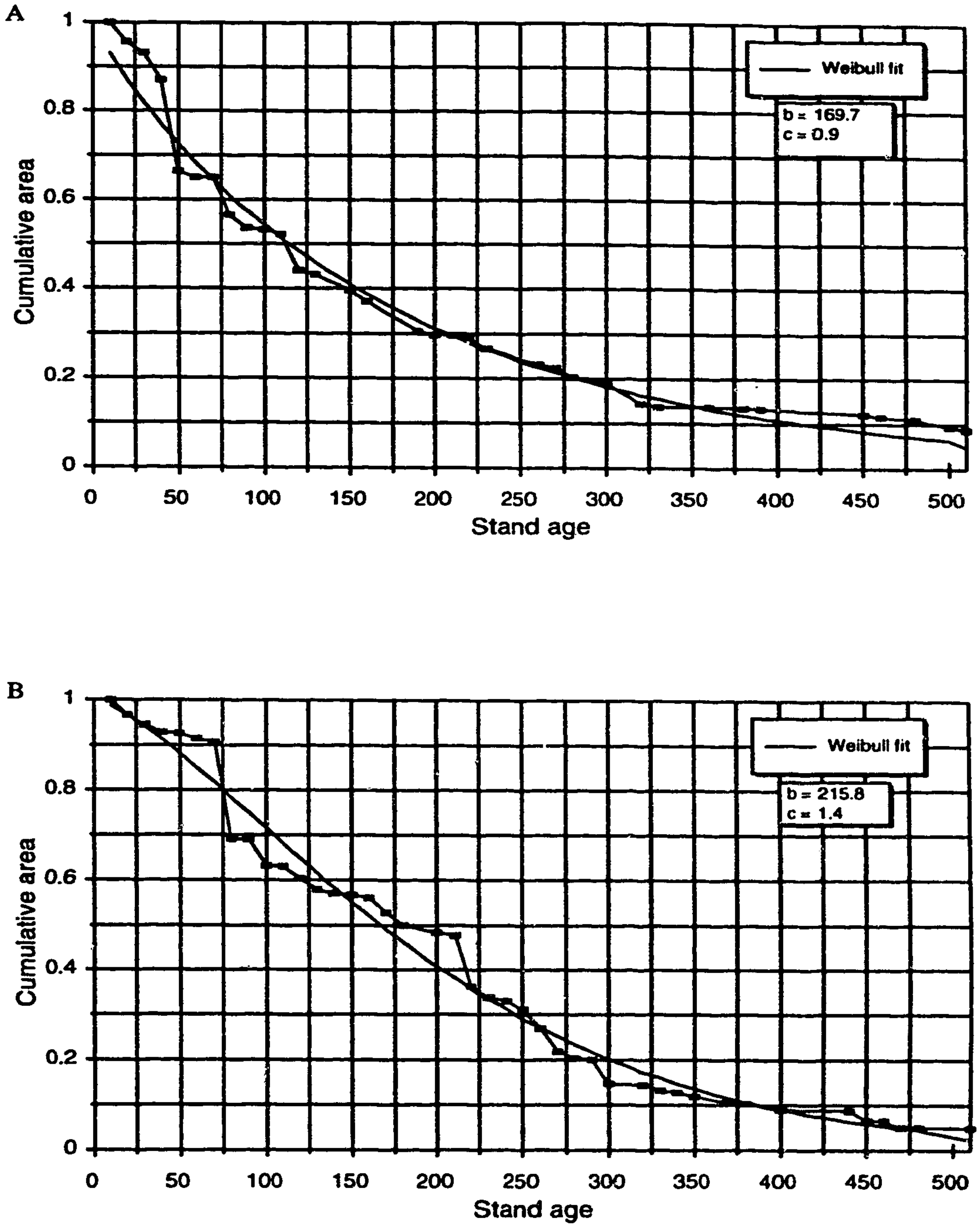

Figure 3.4 Two examples of simulated time-since-fire (survivorship) distributions fitted by the Weibull model for the Boreal fire regime under fire suppression (Scenario 1). Shape (c) and scale (b) values are presented on the graph. The first plot of the distribution is positioned at time 10 to represent the age-class 0 to 10 years.

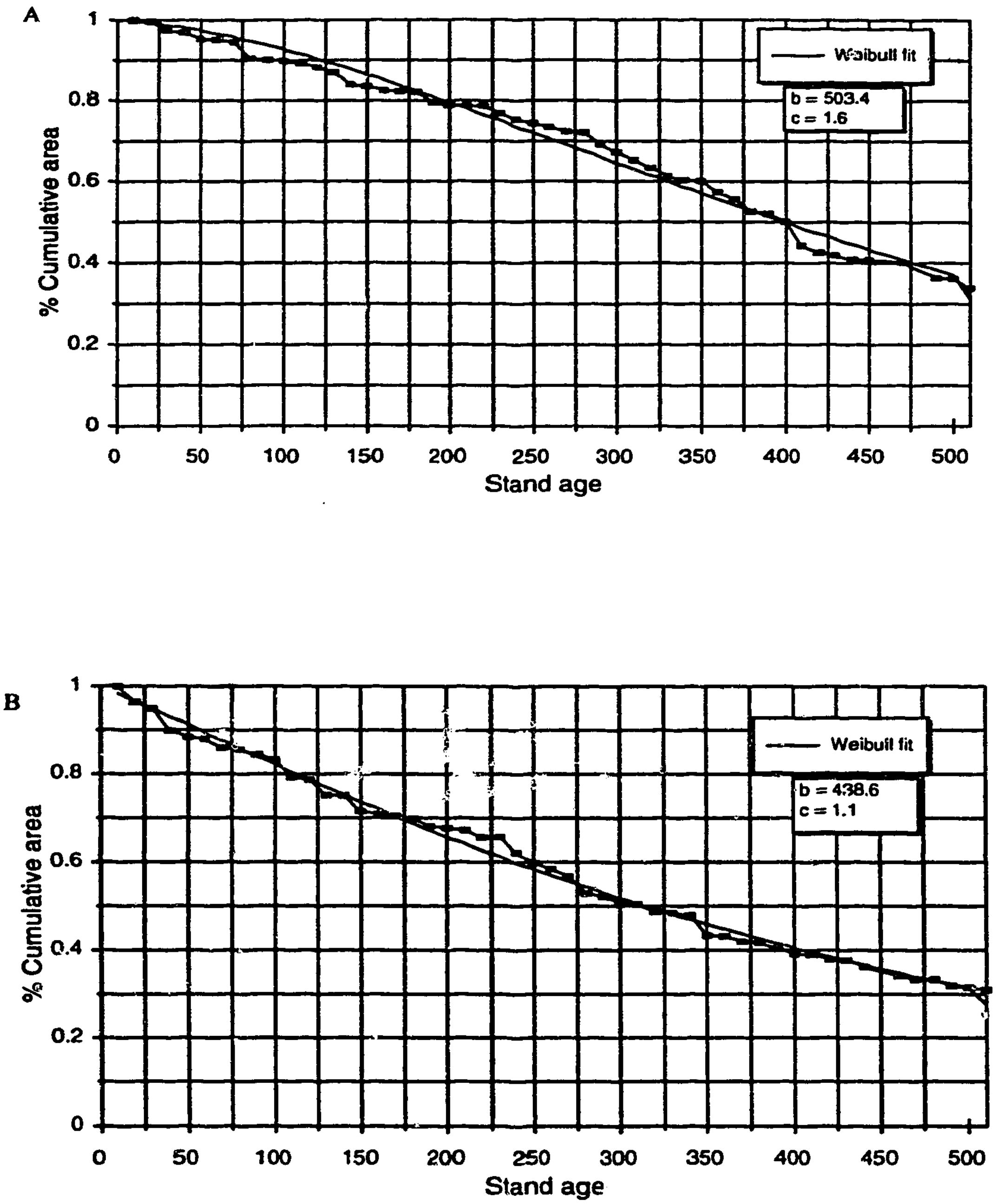

Figure 3.5 Two examples of simulated time-since-fire (survivorship) distributions fitted by the Weibull model for the Mountain fire regime under partial fire suppression (Scenario 2). Shape (c) and scale (b) values are presented on the graph. The first plot of the distribution is positioned at time 10 to represent the age-class 0 to 10 years.

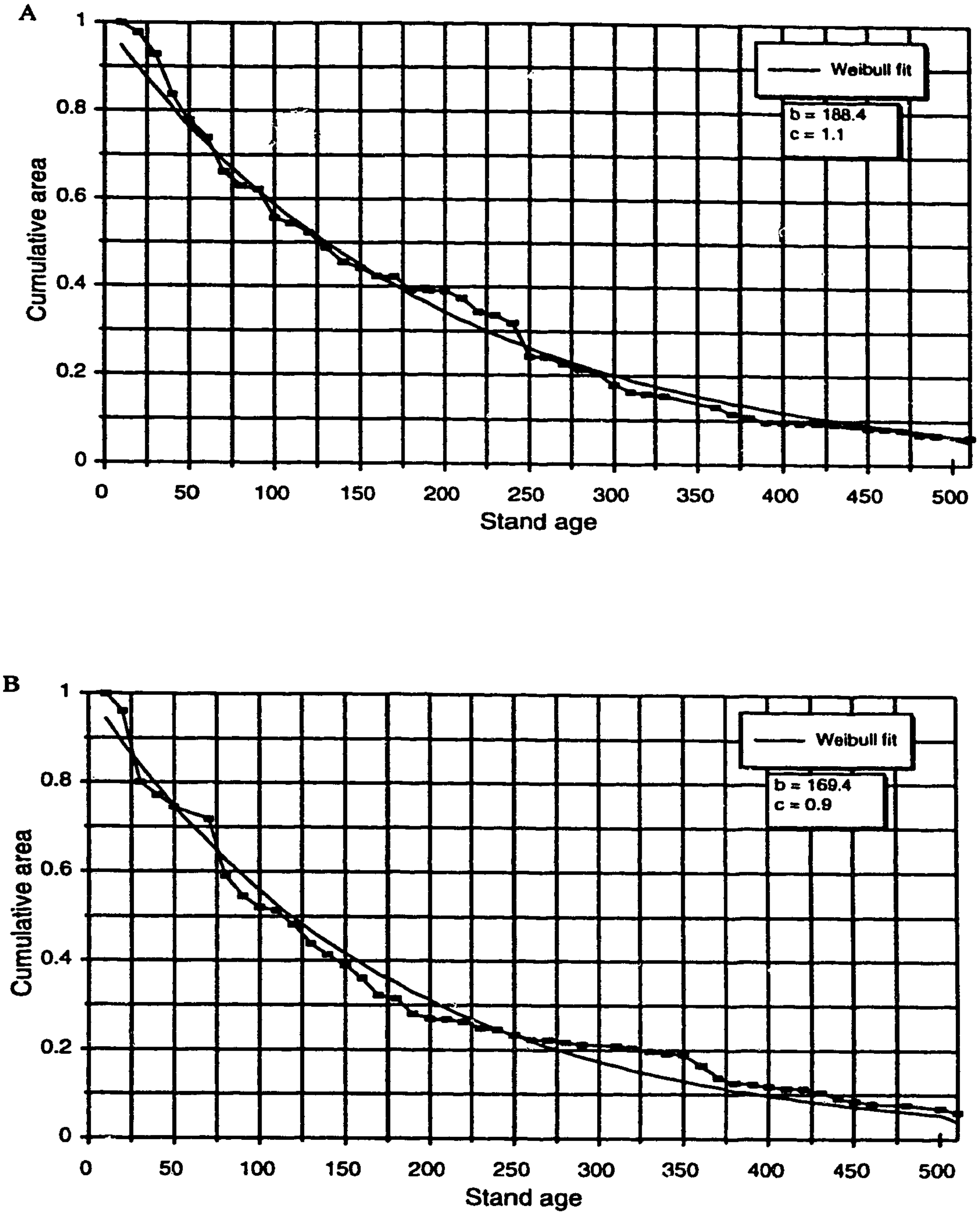

Figure 3.6 Two examples of simulated time-since-fire (survivorship) distributions fitted by the Weibull model for the Mountain fire regime without fire suppression (Scenario 3). Shape (c) and scale (b) values are presented on the graph. The first plot of the distribution is positioned at time 10 to represent the age-class 0 to 10 years.

the variables tested in all cases. Overall, r^2 values ranged from .40 to .84, and only simulations from Scenario 3 had a *Weibull fire cycle* that could estimate the *true fire cycle* or the *average age of the forest* within 25 years for more than 80% of the time. Appendix E provides figures showing the relationship between the paired variables *Weibull fire cycle* and *average age of the forest,* and *Weibull fire cycle* and *true fire cycle*, as well as figures showing the time difference between these paired variables. The values calculated for the *Weibull fire cycle*, the *true fire cycle* and the *average age of the forest* are provided in Appendix F. It should be noted that simulation #21 was removed from the calculations due to its unusually large amount of unburned area, which represented 62% of the study area. The large amount of unburned area resulting from this simulation, produced an outlier in the distribution which greatly reduced the ability of the model to represent the average age of the forest or the true fire cycle.

For all three scenarios, several simulations portrayed changes in slope. Actually, 62% of the simulations from the mountain fire regime without fire suppression, which is the scenario that respected in all terms the assumptions of the model, had survivorship distributions with one or two breaks. Figures 3.10 and 3.11 are examples of simulations with distinct changes in slope. In contrast, Figure 3.12 represents a simulation with one continuous slope (no break).

Table 3.3 Results of the magnitude of variation calculated for discrete data (burn area) and cumulated data (cumulated percent of area) of the first 15 simulations of each Scenario.

	Discrete	Cumulated	Magnitude of variation[a] less than 10% for stands:
Scenario 1: Boreal forest with fire suppression	Min: 65% (age class 120 - 130) Max: 301% (age class 420 - 430)	Variation increased linearly from 3 to 38%.	< 40 years
Scenario 2: Mountain regions with partial fire suppression	Min: 35% (age class >500) Max: 154% (age class 460 - 470)	Variation increased linearly from 1 to 14%.	< 260 years
Scenario 3: Mountain regions without fire suppression	Min: 35% (age class >500) Max: 143% (age class 490 - 500)	Variation increased linearly from 4 to 36%.	< 80 years

a: the magnitude of variation of survivorship distributions (cumulative form).

Table 3.4 Results of the ability of the Weibull model to estimate the true fire cycle and the average age of the forest.

	Weibull fire cycle / true fire cycle	Weibull fire cycle / average age of the forest
Scenario 1: Boreal forest with fire suppression (n = 50)	t-test rejected equality $r^2 = .56$ ± 25 yrs: 59%[a]	t-test rejected equality $r^2 = .84$ ± 25 yrs: 70%
Scenario 2: Mountain regions with partial fire suppression (n = 49)	t-test failed to reject equality $r^2 = .40$ ± 25 yrs: 35%	t-test rejected equality $r^2 = .56$ ± 25 yrs: nil
Scenario 3: Mountain regions without fire suppression (n = 25)	t-test rejected equality $r^2 = .53$ ± 25 yrs: 92%	t-test rejected equality $r^2 = .71$ ± 25 yrs: 96%

a: read as: for 59% of the simulations, the Weibull fire cycle could predict within 25 years the true fire cycle.

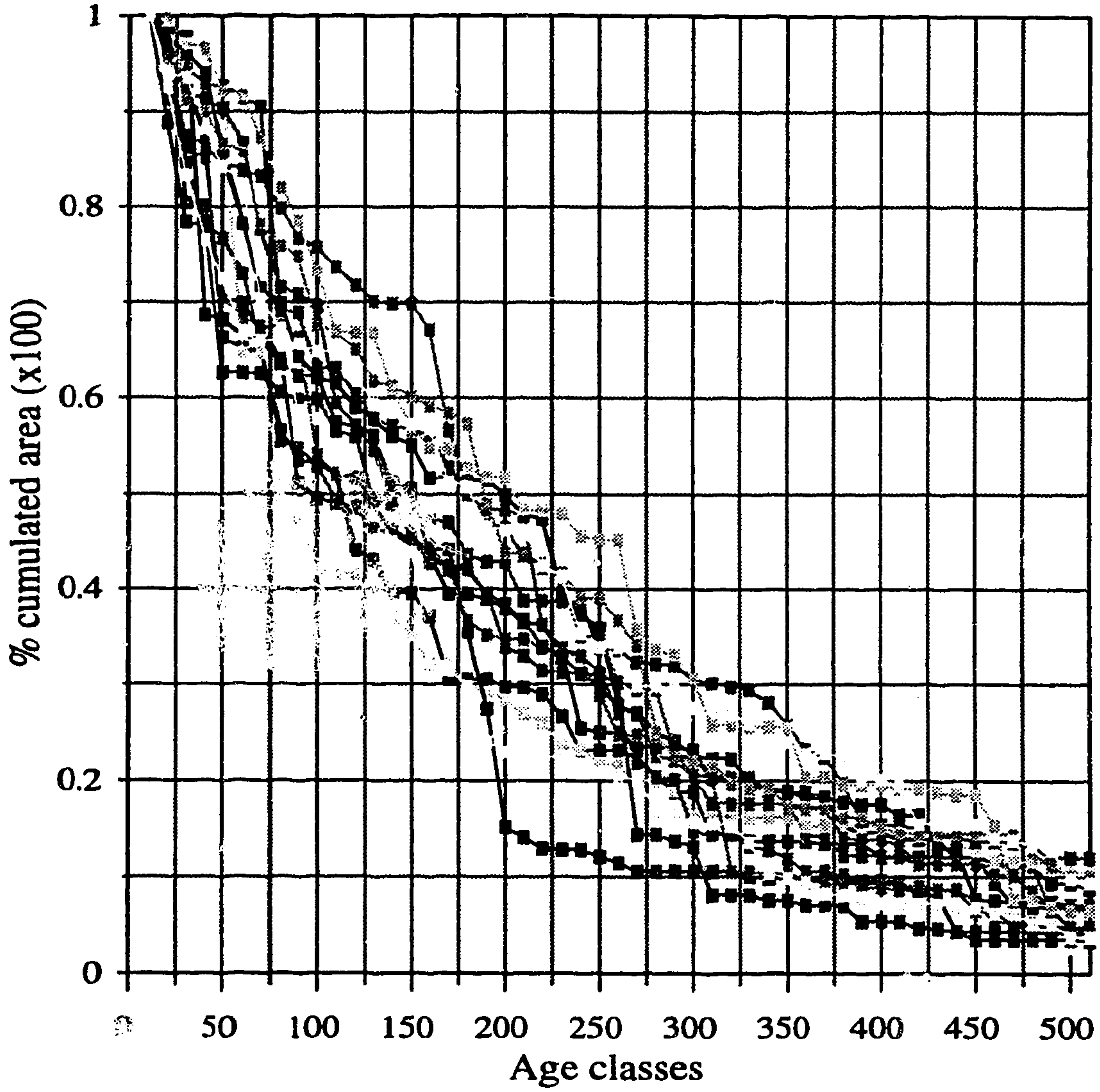

Figure 3.7 Magnitude of variation of first 15 simulated survivorship distributions plotted for the Boreal fire regime under fire suppression (Scenario 1).

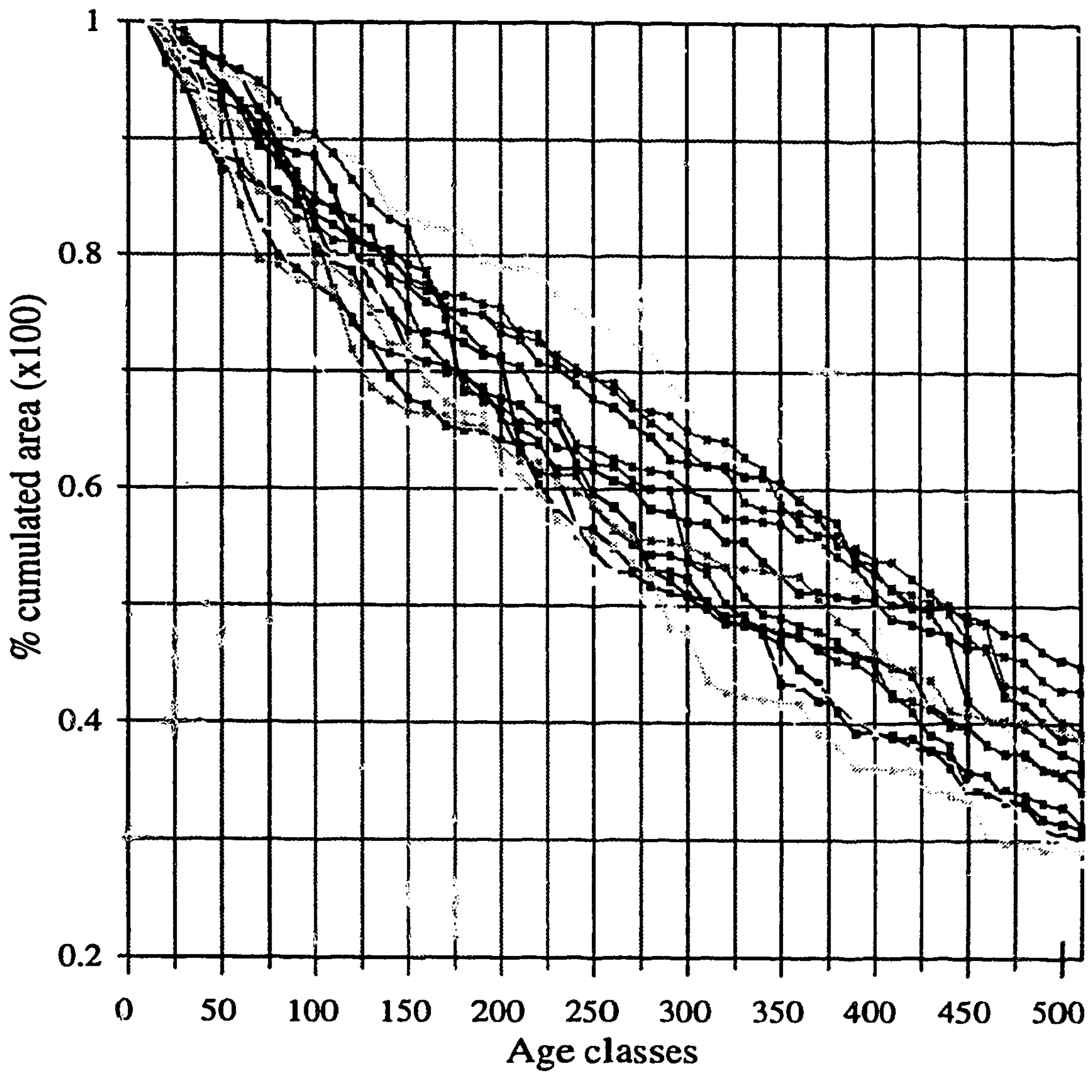

Figure 3.8 Magnitude of variation of first 15 simulated survivorship distributions plotted for the Mountain fire regime under partial fire suppression (Scenario 2).

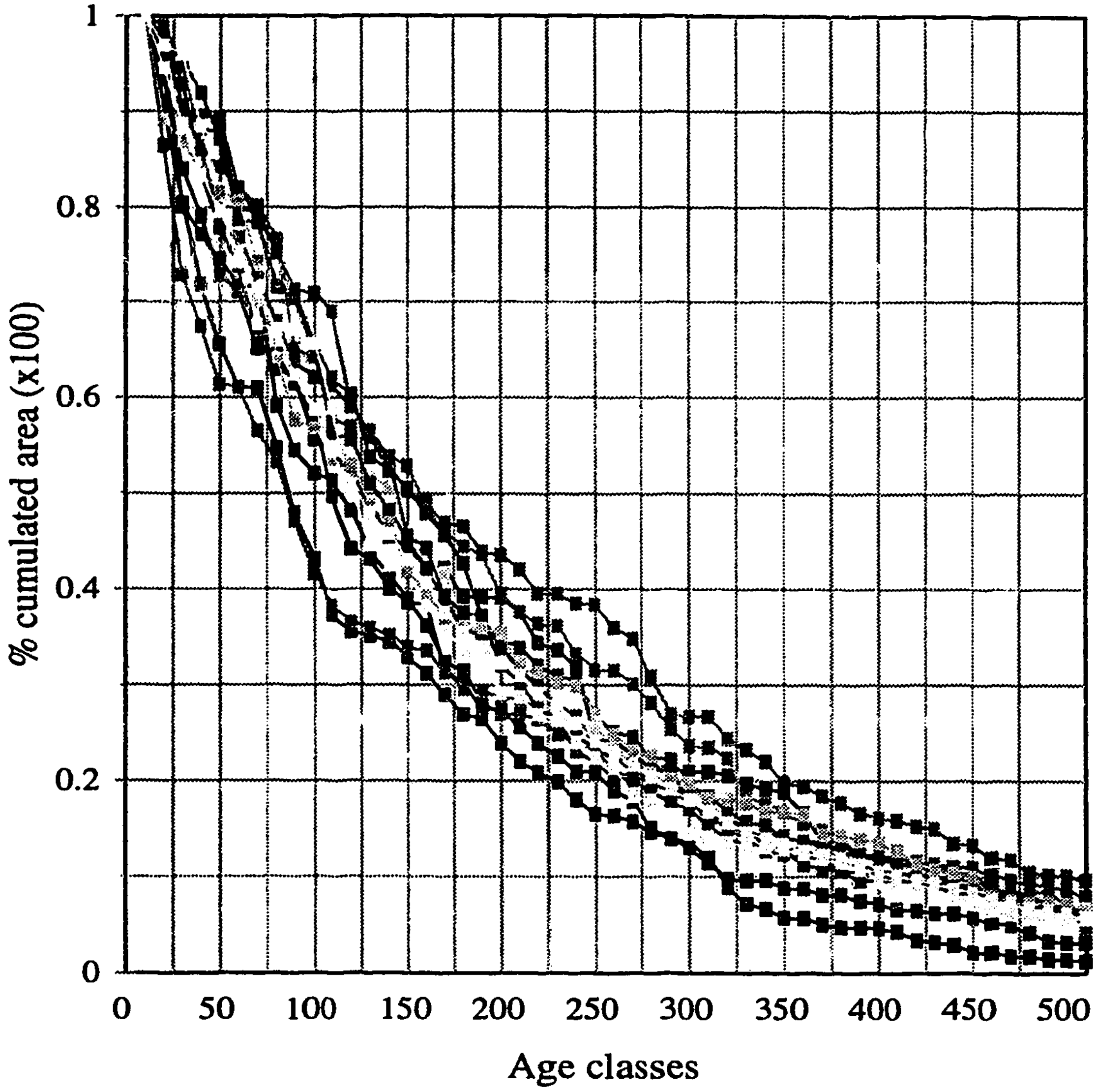

Figure 3.9 Magnitude of variation of first 15 simulated survivorship distributions plotted for the Mountain fire regime without fire suppression (Scenario 3).

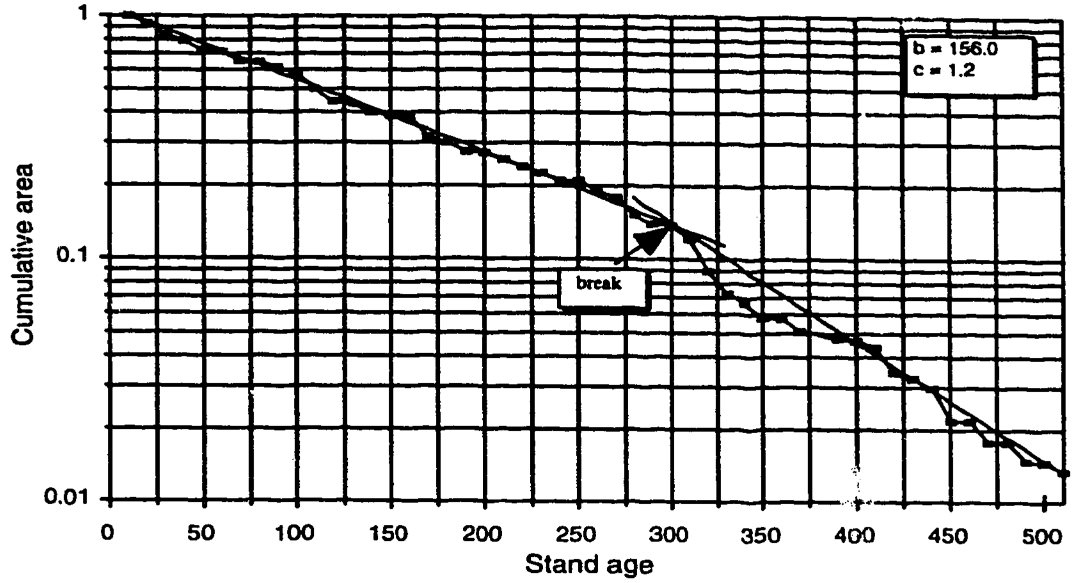

Figure 3.10 Simulation from Scenario 3, showing one change (a break) in slope.

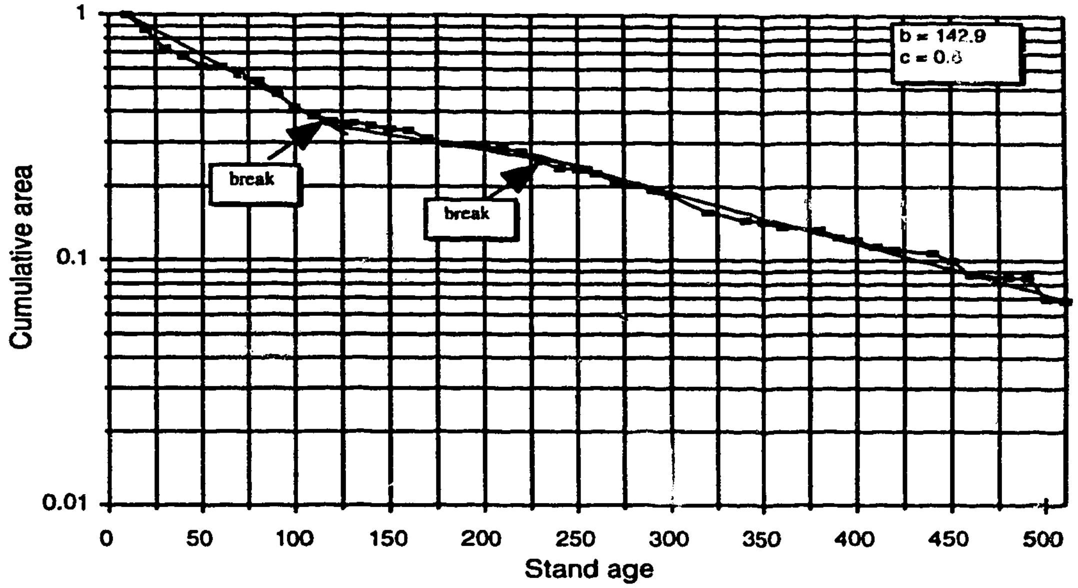

Figure 3.11 Simulation from Scenario 3, showing two changes (break) in slope.

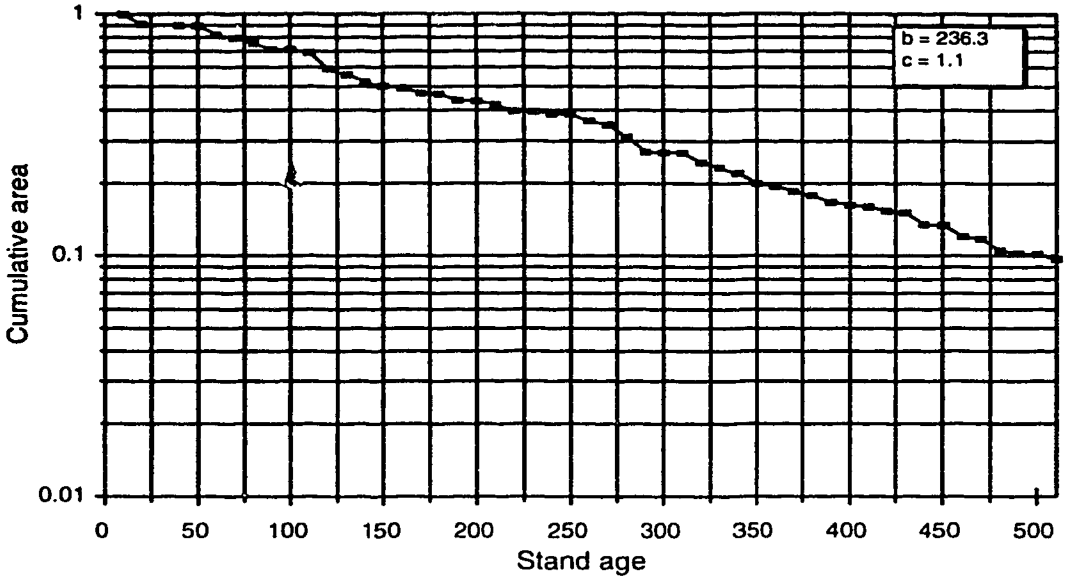

Figure 3.12 Simulation from Scenario 3 plots as a straight line and does not show any change in slope.

3.4 Discussion

Most of the distributions from the three Scenarios were well fitted by the Weibull model, even though in all simulations, some areas did not burn. The amount of unburned area was mainly attributed to the type of fire regime modelled, but also, to some extent, to two of the three limitations of the fire simulation program. These were:

1) Fire spread was not confined to the boundaries of the study area. Although this feature might have contributed to some extent to the increase of unburned cells, it had to be implemented to match reality. It is well known that fires that start in an area will burn outside that area, and the reverse is true, as fires do not recognize managerial or political boundaries unless they are defined by topographic or physical features which inhibits fire spread. However, as a result of a limitation of the program, no external fires burned into the

study area. This likely contributed to the number of unburned cells.

2) The random spatial distribution of fires is likely not realistic, especially for mountainous areas where environmental factors such as terrain, vegetation and weather are known to affect fire distributions (Barrows 1951). The distribution of lightning also varies over large areas and current research from Banff National Park (unpublished data) has found that lightning ignitions can be almost non-existent in some mountain zones. Similar results have been reported by Van Wagtendonk (1991). Furthermore, human use patterns are also known to affect the location and number of fire starts. Highly used areas are more prone to fire (White 1985). Additionally, other biotic and abiotic factors that are peculiar to specific areas may also influence periodicity and extent of burning. Specifically, site quality and vegetation use by animals, insects and diseases may affect the fire regime in an area. Hence, the probability of burning is affected by several factors, which are not accounted for by the methodologies used in this study.

The complexity of the factors and processes that impact on fire distribution are highly variable over time and space. This greatly impacts on our ability to demonstrate that the probability of burni [illegible] ses as a forest stand matures. As an example, one might think that older stands would be more prone to fire due to the accumulation of fuel on the ground. However, older stands generally means greater fuel compaction and wetter conditions due to the greater occurrence of large diameter logs, which tend to shelter the soil and the organic on it. These two conditions tend to reduce the fuel availability which, in turn, slow burning and inhibit fire spread. The combination of variables affecting fire start and spread can be large, and all these factors can affect fire size and distribution. A list of the main factors would include: 1) time of the year, 2) number of days without rain, 3) relative humidity, 4) temperature, 5) wind, 6) vegetation type and composition, 7) fuel load, arrangement, continuity and moisture, 8) terrain features such as: aspect, elevation, slope, 9) fuelbreaks: rock outcrops, lakes, roads, and 10) other disturbances such as: insect kills, blow-down, and avalanche. The decision making process accounting for the probability of burning over space is labourious and probably not that accurate. To facilitate the experiment and to meet the criteria of homogeneity in the study area (see Introduction), every cell was assigned an equal chance of being ignited, and all had the same probability of burning.

3) No elevation, aspect, slope, vegetation or fuelbreak cover maps were used to govern fire sizes, although it is well known that fire size is influenced by these variables (Barrows 1951). However, factors that limit fire spread were implicitly accounted for by using fire sizes determined from documented fire statistics. For example, in the mountains, fires tend to stay small due to the fact that almost 50 % of the area is composed of rock and ice. Therefore, it is believed that fire growth is usually constrained by the presence of these fuel free areas. Hence fires in mountain areas are usually contained in one or two valleys.

Multiple simulations allowed estimation of the likely variation around each age-class as the stand lives through time. This is something that is impossible in actual field studies. It was found that the present-day survivorship distribution in all cases could not adequately represent a common survivorship behaviour of forest stands to fire. Survivorship curves fluctuated by more than 10% over a 500 year period, and this fluctuation increased as forest stands became older. Specifically, the proportion of different age stands that survived fire was not the same 300 years ago as it is now. This is due to the fact that as one goes further back in time, fires have more time to overlap and partly or totally erase previous burns; thus increasingly changing the landscape mosaic. The rate at which the landscape mosaic will change is impacted by the size and frequency of burning as the simulations clearly demonstrated. In the case of the Boreal fire regime, where large fires more quickly erase past fire evidence, survivorship distributions were reliable for only a short period of time of about 30 to 40 years. The most reliable survivorship curves will likely come from a fire regime characterized by small size fires and low fire frequency such as in Scenario 2 (Mountain fire regime with partial fire suppression).

Results from Scenario 2 suggest that survivorship curves can be reliable for up to 250 years. Although the Mountain fire regime without fire suppression (Scenario 3) had small sized fires as well, the increased frequency in burning greatly reduced the reliability of the survivorship distribution. The fire regime of this case study can only be evaluated with confidence from stands younger than 80 years in age.

It was also determined that the analysis of survivorship should be done cumulatively, rather than looking at the amount of burn area by age-classes. The magnitude of variation for the burn areas was much greater than that for the cumulative form. For Scenarios 1, 2 and 3, the variation for burn areas was more than 100% for 80, 30 and 53% of the age-classes, respectively. Thus, no reliable information could be inferred from such data.

It is interesting to note that the t-test found the *Weibull fire cycle* to be equal to the *true fire cycle*, while only 35% of the time could the *Weibull fire cycle* predict the *true fire* *cycle* to within 25 years. Since the paired t-test did not appear to be credible, in this case, for management purposes, only the r^2 values and percent of simulations able to predict the *true fire cycle* or the *average age of the forest* to within 25 years, were considered as a decision making guideline.

Results from the three scenarios showed very nicely the need to respect the scale of space and time, which are the two basic assumptions of the Weibull model. A fire cycle too long relative to the length of time represented by fire history data will prevent the model from being able to estimate the fire cycle or the average age of the forest, as was the case for Scenario 2. In Scenario 2, occasionally less than one fire cycle was depicted during the simulation run time of 500 years. This was due to the small number of fires and the small size of those, which resulted in simulated fire cycles ranging between 300 and beyond 500 years.

Similarly, a study area too small in comparison to the size of the burns, as turned out to be the case for Scenario 1, will also result in a poor ability of the model to estimate the fire cycle or the average age of the forest. Johnson and Gutsell (1994) had suggested that the chosen area be at least 3 times bigger than the biggest possible burn area. However, the results of this research suggest that the study area should be at least 15 to 20 times bigger than the largest possible fire occurring in that area. This is corroborated by the work of Boychuk *et. al.* (1995) and Charlie Van Wagner (personal communications). However, this study was not designed to determine the exact size of an area.

Scenario 3, which respected in all terms the model's assumptions, was characterized by a fire regime that yields to about 3 fire cycles per 500 year period and a study area 17 times bigger than the largest occurring fire. It would appear that when the time and scale assumptions are respected for a homogeneous study area, the model is indeed capable of estimating the fire cycle or the average age of the forest to within 25 years. Furthermore, these survivorship distributions will tend to plot as a negative exponential distribution ($c = 1$). In the analysis of real life data, it is very important to stress that only when all the assumptions and criteria are met, can one use the average age of the forest as a surrogate for fire cycle. Otherwise, the Weibull fire cycle is incapable of estimating the fire cycle or the average age of the forest. Therefore, even if a survivorship distribution happens to be well modelled by the negative exponential, one should not be too hasty to substitute the average age of the forest for the fire cycle.

A new approach to interpret fire history data

Before commencing this portion of the Discussion, it must be stressed again that in theory a constant fire regime is reflected by the negative exponential form, which plots as a descending straight line on semi-logarithmic paper (Van Wagner 1978, Johnson and Gutsell 1994). A change, or a break in the slope of the distribution has been interpreted as a change in the fire regime, that is, a change in the fire cycle (Johnson and Gutsell 1994, Johnson *et. al.* 1995). It must also be said that the identification of a change in slope is up to the discretion of the interpreter. Testing the statistical significance of a change in slope (a break) in the age-class distribution is further complicated by the fact that there is no replication in data. These replications would provide the measure of variation required to test for significance.

These results have shown that it is in fact common to observe changes of slope in a survivorship distribution. Although the simulations had a constant fire regime and were not influenced by external factors such as climate, topography, or human use, changes in slope of time-since-fire distributions were still observed. Therefore, it would seem that what was identified as a change in the fire regime due to climate for the fire history studies from Kananaskis Country, Glacier and Kootenay National Parks (Johnson *et. al.* 1990, Masters 1990, Johnson and Larsen 1991), cannot be substantiated. Hence, current methods of fire history analysis, as described by Johnson and Gutsell (1994), which consist of calculating a fire cycle for each slope identified on the survivorship distribution, are questionable.

In addition, the large magnitude of variation observed for simulated survivorship distributions from either scenarios, is a reminder that shapes of distributions will also change with time even though the fire regime may remain constant. Therefore, the present-day survivorship distribution that is obtained from real time-since-fire data does not provide adequate information on the fire regime to allow us to evaluate the changes in the fire regimes attributed to changes in slope. In other words, the number of samples (n = 1) is not large enough to allow us to draw any inferences regarding the fire regime of an area. The two last statements are even more true if the study area is small compared to the size of fires.

This research suggests that perhaps unequal fire sizes, an outcome of spatial dependency of forest stands to fire, contributes to the magnitude of variation among distributions and to changes in slope in the distribution. The Weibull or negative exponential models must be applied to spatially independent data, which assume that the forest is composed of equal size stands (landscape units) that are independent of one another (Van Wagner 1978, Boychuk *et. al.* 1995). However, in real life, this assumption does not apply to burn areas. Burn patches vary in size because forest stands (landscape units) located in proximity and stands downwind or up slope from the burning unit will have a greater chance of burning. This makes each landscape unit spatially dependent, and spatial dependency of forest stands affects the rate at which the study area is burned. By varying fire sizes in the simulations, spatial dependency was accounted for to some extent. Results from this research are consistent with the recent work of Boychuck *et. al.* (1995) who found that there exists significant variability in boreal landscape when fire size and fire frequency vary over time.

3.5 Conclusion

Variations in survivorship patterns are expected, which means that the present-day survivorship distribution is not all that reliable for analysing fire regimes. Further, changes in slope of the distribution should not be interpreted as a change in the fire regime. The Weibull model was able to estimate the fire cycle for the area only when the study area respected the assumptions of the model: random distribution of fires, large study area in comparison to fire sizes, and short fire cycle in comparison to the time period covered by fire history data.

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CHAPTER IV

Conclusion

4.1 Conclusions and recommendations

1. The interpretation of the fire regime from a present-day time-since-fire distribution was estimated to be reliable for only a short period of time into the past, which varied based upon the fire regime modelled. Size and frequency of fires, two elements characterising the fire regime, were attributed to the significant variability found in age-class distributions. The conclusion is that the best way of identifying the current fire regime of a specific area, is not by using a survivorship curve but by keeping track of historical fires in the area and by documenting fires based on their frequency, size, intensity, cause and location. This procedure is a prerequisite to ensuring homogeneity of the study area when using the Weibull fire history model. If landscape partitioning to assess the magnitude of survivorship distributions for a certain region is attempted, managers must ensure that all landscape units are large enough and are regulated by the same fire regime.

2. The shape of the distribution of forest survivorship to fire does not suggest any kind of probability of burning related to the age of the forest. Through a constant fire regime, where ignition is random and age independent, shape of distributions are expected to vary due to the significant variability found in age-class distributions.

3. Changes in slope of the time-since-fire distribution were not attributed to changes in the

fire regime, and hence, changes in the fire cycles. Changes in slope in time-since-fire distributions are expected and are believed to be attributed to the spatial dependency among landscape units, which affects the variability of survivorship patterns.

4. The Weibull and negative exponential models are not recommended for use on areas that do not respect the basic assumptions of the models. The key elements to respect are a homogenous study area that is large enough, and where time-since-fire data go as far back in time to estimate at least three fire cycles. Fire distribution must be assumed random and unreliable data should likely be removed from the analysis. A failure to respect any of these criteria will result in very poor accuracy from the Weibull or negative exponential model in estimating the fire cycle. If the criteria or assumptions are not met, the average forest age is probably a more informative statistic, than using something that will be misleading.

5. The validity of using the Weibull model to predict the fire cycle, especially in the mountains, is questionable. Since a fire cycle is unique to each study area due to different factors governing the fire regime, it seems ineffective to produce an equation that models a survivorship distribution applicable to only one specific area. Thus, the equation can only be used once, and a new equation must be produced for each landscape unit. This statement is more true in the mountains where we know that fire is not random and that the fire cycle varies spatially throughout the landscape. The use of this lifetime model has been mistakenly extrapolated beyond its original use to model survivorship or mortality of species, and the failure rates for mechanical parts (Lawless 1982). As an example, collecting samples of ages

of numerous trees of a certain type, and that, for several independent locations, can be used to build mortality and survivorship curves. These curves, which are used to predict the life expectancy or mortality rate of that tree species, are useful as they are applicable to a wide range of study areas. Models that can only represent one study area under one set of conditions are of little scientific value.

6. For the mountain regions, the value of using a fire cycle that applies to the entire study area for a forest fire management tool is also debatable. The inverse of the fire cycle is used to determine the annual percent burn of the managing area (Johnson and Gutsell 1994), but the inherent problem of using such a fire cycle for management is that it does not identify where the burning has or should occur. The fundamental question in fire management remains: "Should fires be randomly distributed or repeated within a particular landscape unit of the management area?". A fire cycle value attributed to the entire study area likely reflects an average fire cycle. Some parcels of land rarely burn, while others are more frequently disturbed and should be represented by a much shorter fire cycle. The fire cycle is associated with the probability of burning an area which changes spatially over the landscape and through time.

In conclusion, if a fire cycle cannot be calculated for the study area due to the impossibility of respecting the criteria or assumptions stated above, the average age of the forest should be employed as a management tool. Fire managers should plan burns and manage wildfires in a way to keep the present-day average forest age, or a pre-defined average age and stand structure, with a distribution in the age cohorts of forest stands as represented by the survivorship distribution.

4.2 Literature cited

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CHAPTER V

Future Research

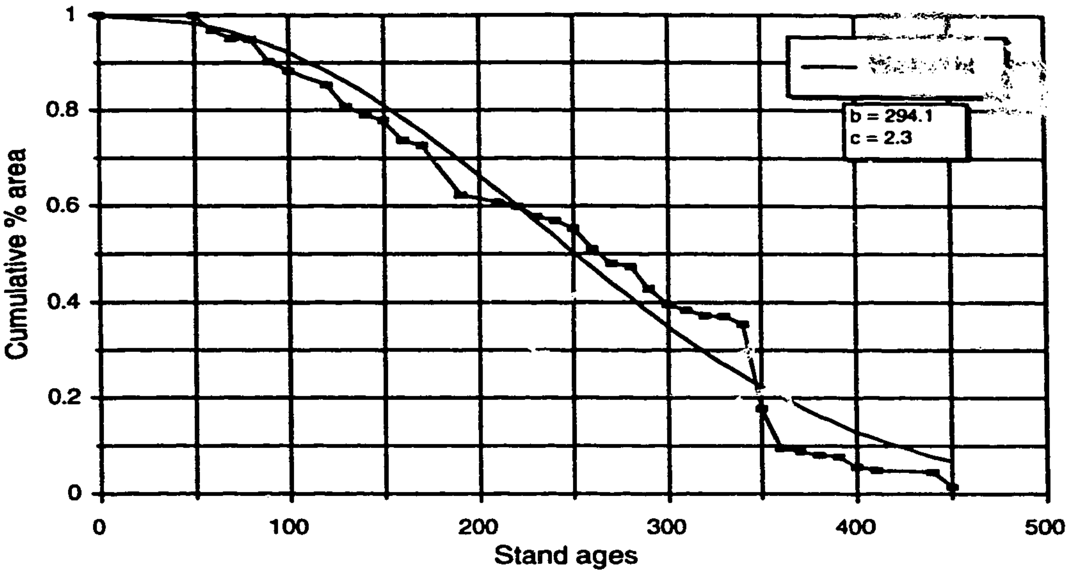
As a result of this study, I have concluded that there needs to be more research in the following two areas:

1) Results of this research recommend pursuing the use and development of fire simulation programs to estimate the fire cycle of a region. The use of realistic parameters as the foundation of the simulation program worked well to replicate the fire regime of Banff National Park. However, a more sophisticated fire simulation program could account for probabilities of burning if the proper data layers are used. Further research is therefore required in the field of probabilities of burning in relation to terrain. This is a crucial aspect to fire management in mountain regions, where probabilities of burning are highly variable over the landscape. It is suspected that each parcel of land under a similar combination of terrain variables such as aspect, elevation, valley orientation, would display a similar survivorship distribution if those parcel of lands are subject to the same fire regime. I have undertaken research on the effect of terrain on burning probabilities in Banff National Park, and hopefully this new knowledge will increase managers' capabilities to estimate a more useful local fire cycle rather than a broad landscape fire cycle.

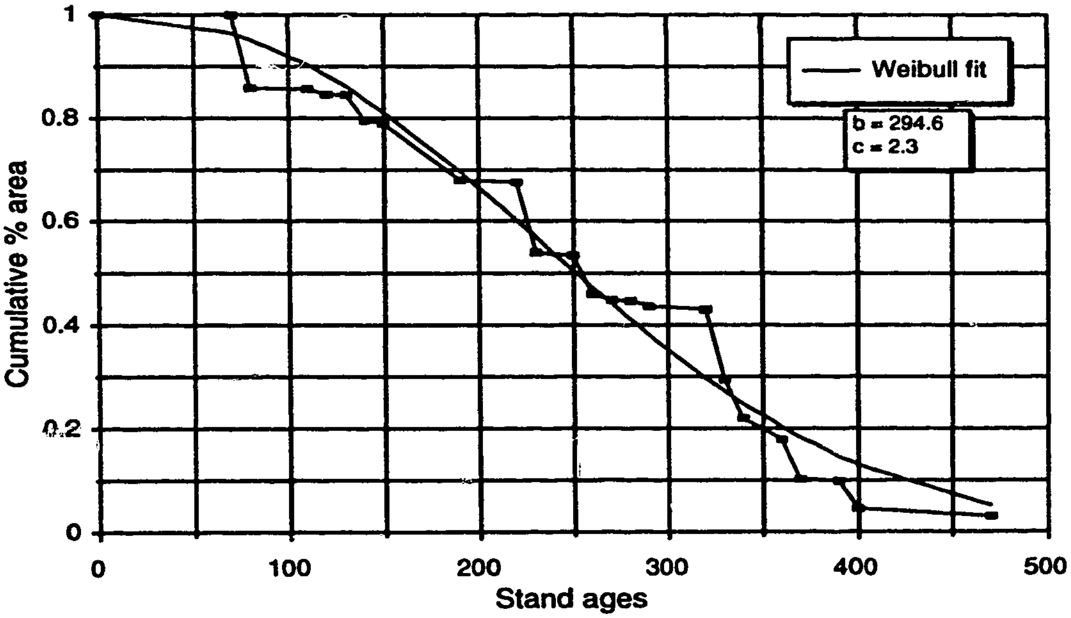
2) To enhance the accuracy of the Weibull model in predicting the fire cycle, aging of older stands must be reliable. To do so, better methods of fire history data collection should be investigated. For example, dating from charcoal found in lake bottom sediments using the frozen core method, and used in conjunction with tree aging, could increase the accuracy of the fire year from old forest stands that are believed to have originated from fire.

APPENDIX A

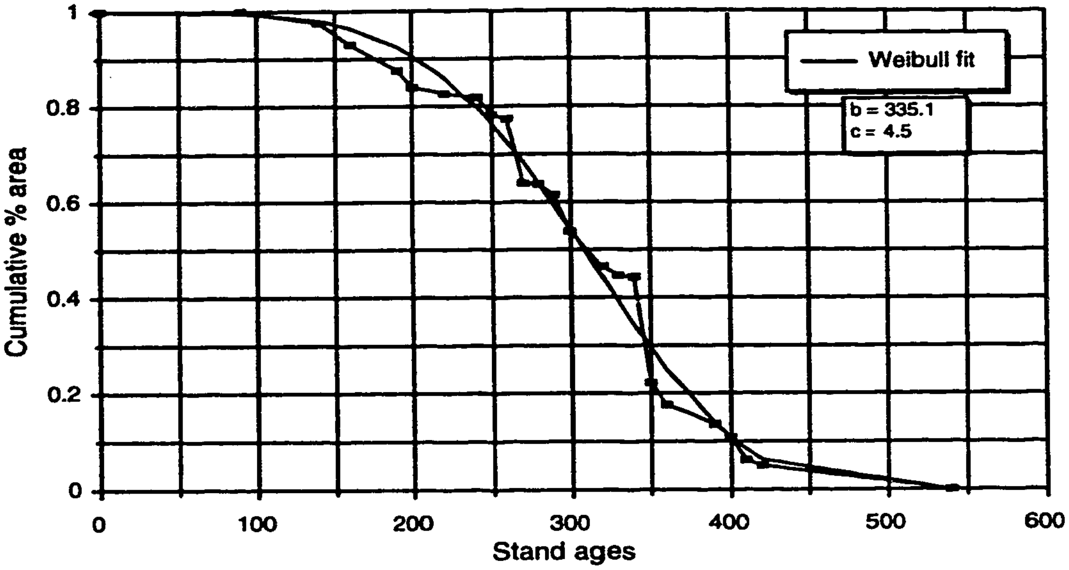
Time-since-fire distributions for the main drainages of Banff National Park



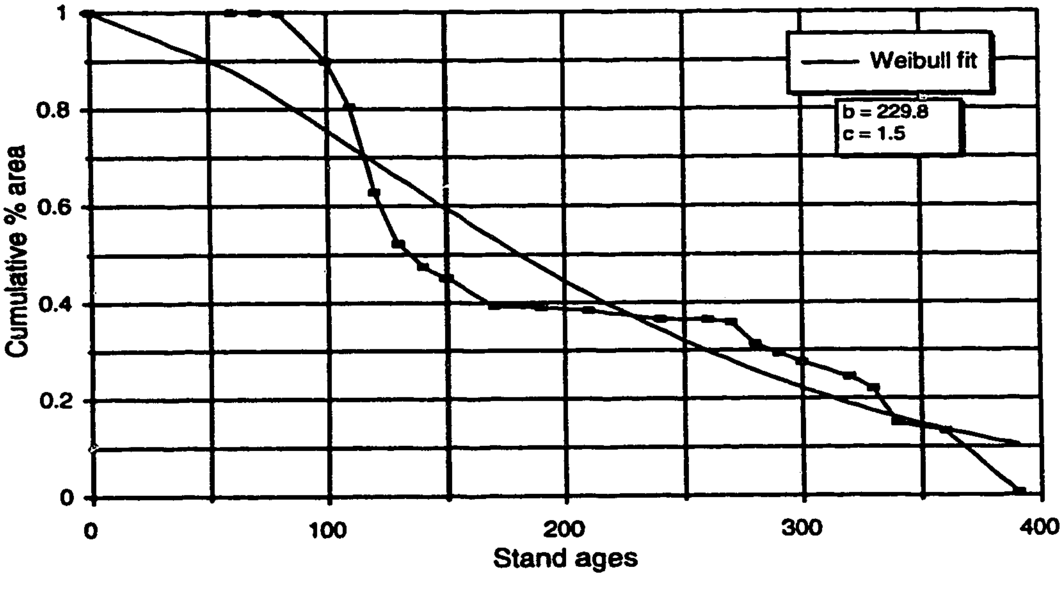
Time-since-fire distribution for the North Saskatchewan basin.



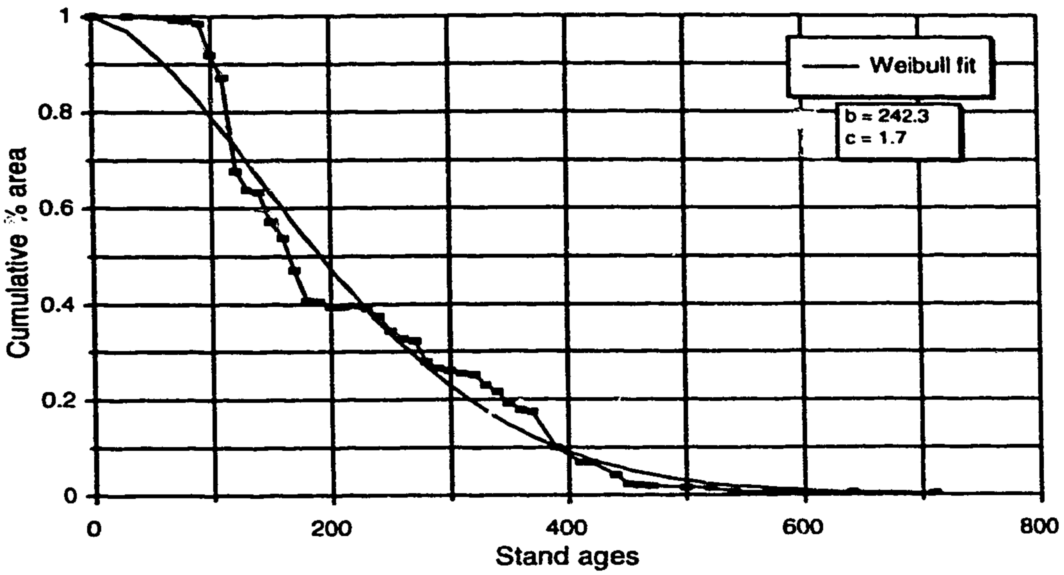
Time-since-fire distribution for the Red Deer basin.



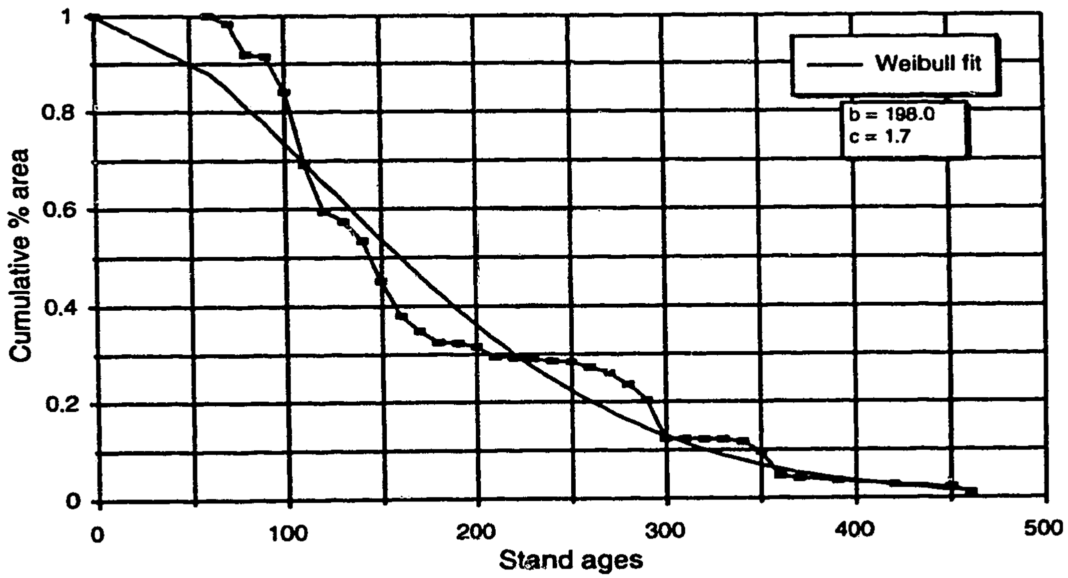
Time-since-fire distribution for the Clearwater basin.



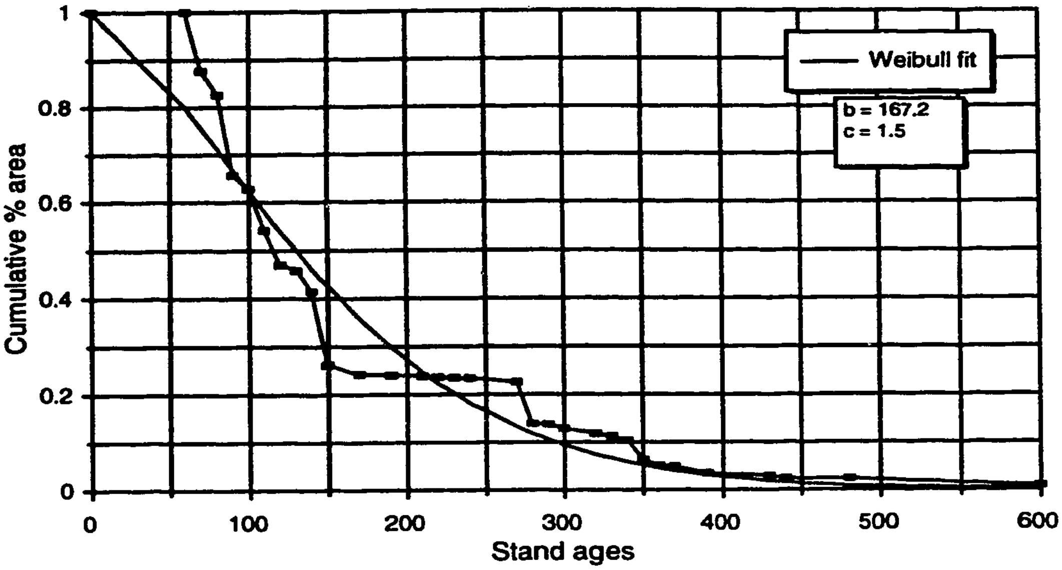
Time-since-fire distribution for the Panther basin.



Time-since-fire distribution for the Middle Bow basin.



Time-since-fire distribution for the Lower Bow basin.

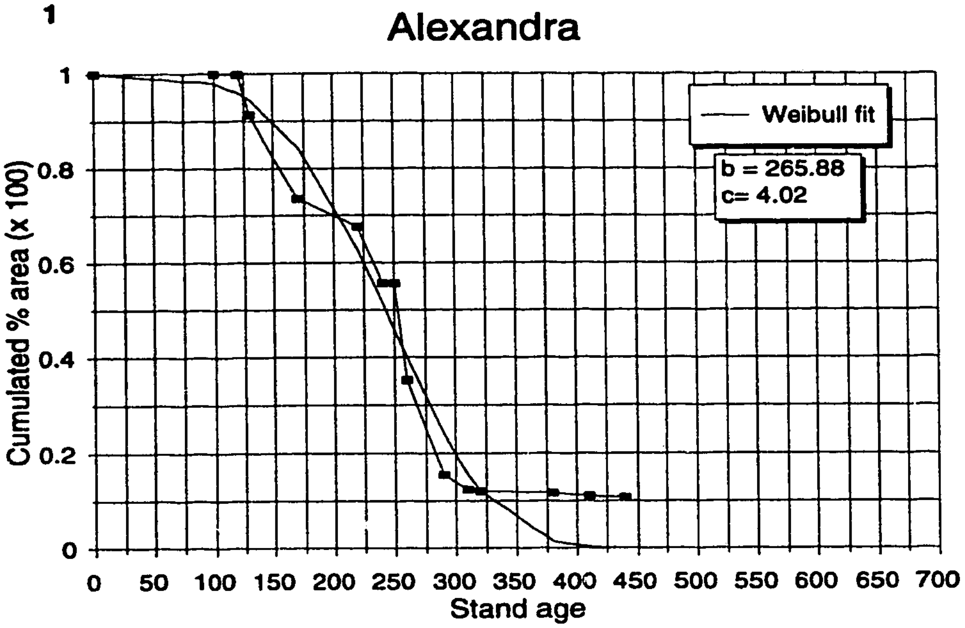


Time-since-fire distribution for the Cascade basin.

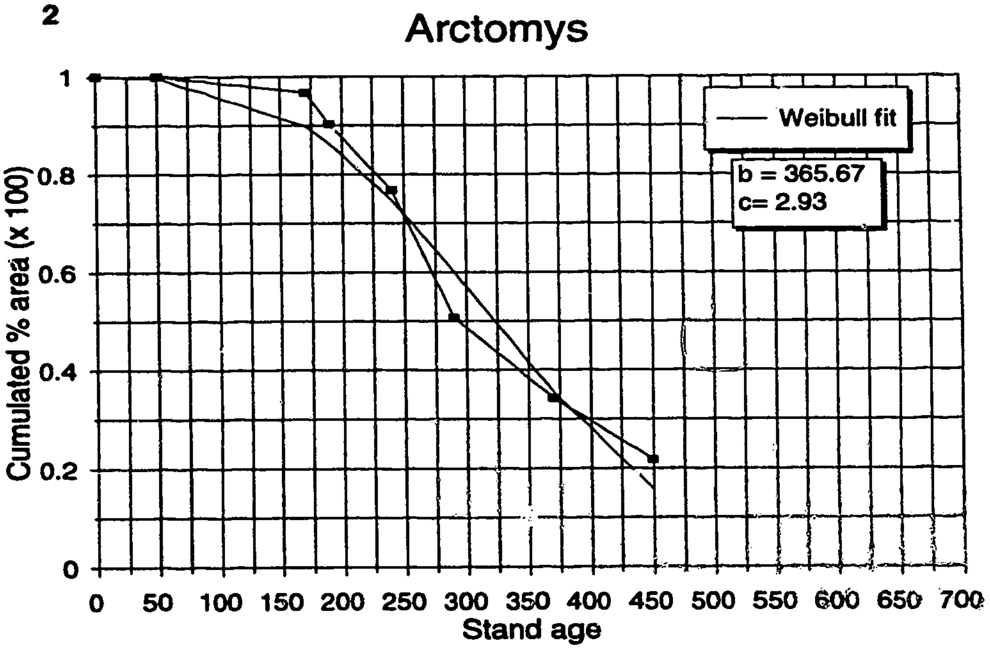
APPENDIX B

Time-since-fire distributions for the watersheds of Banff National Park

1


Alexandra
Weibull fit
b = 265.88
c= 4.02
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

2


Arctomys
Weibull fit
b = 365.67
c= 2.93
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
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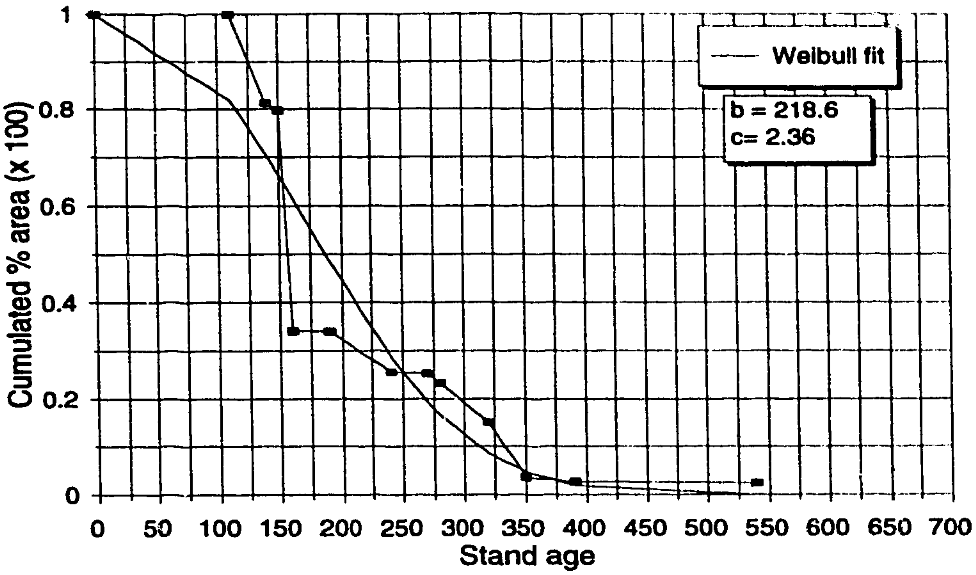
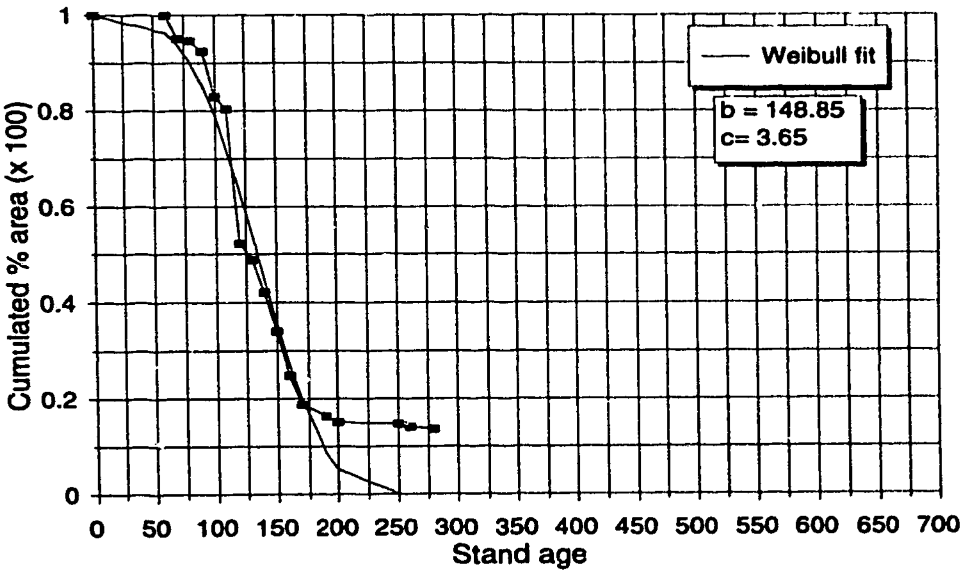
300
350
400
450
500
550
600
650
700
Stand age

3

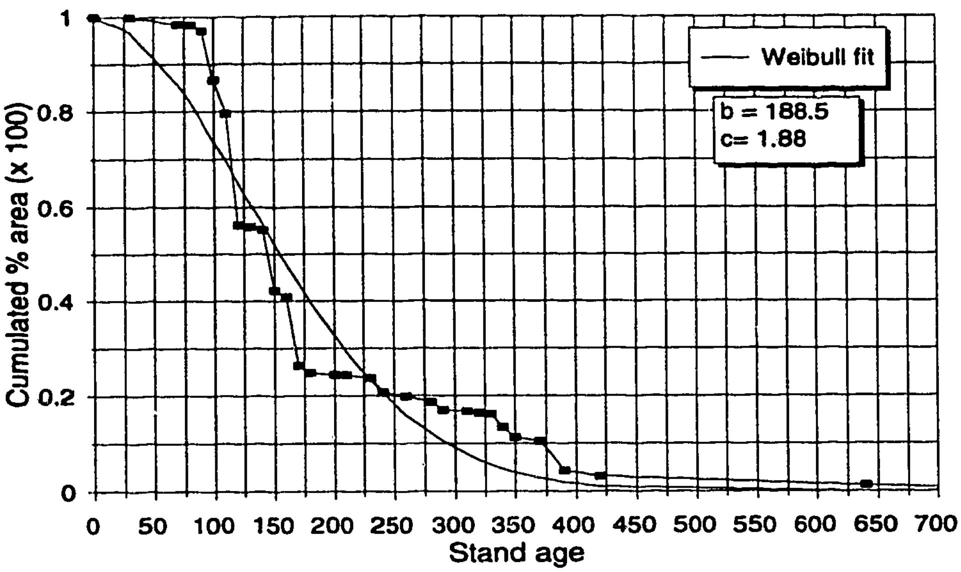

Baker

4


Lower Bow

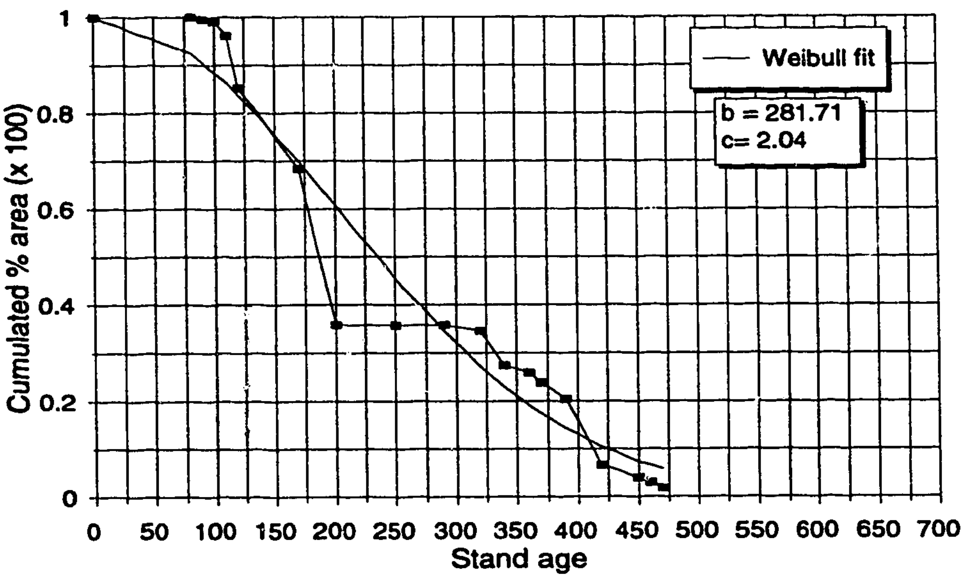
5

Middle Bow

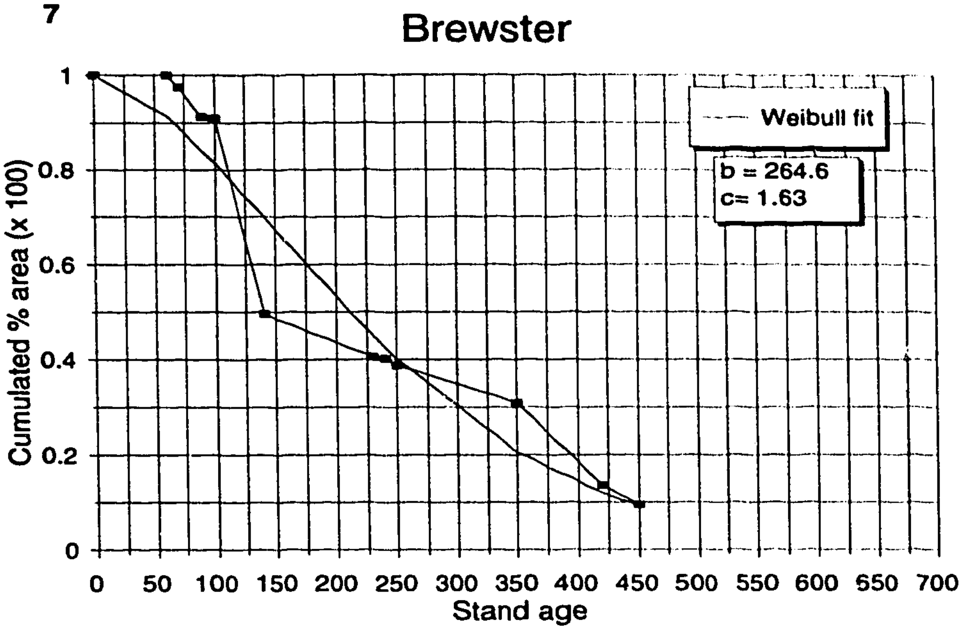


6

Upper Bow



7


Brewster
Weibull fit
b = 264.6
c= 1.63
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
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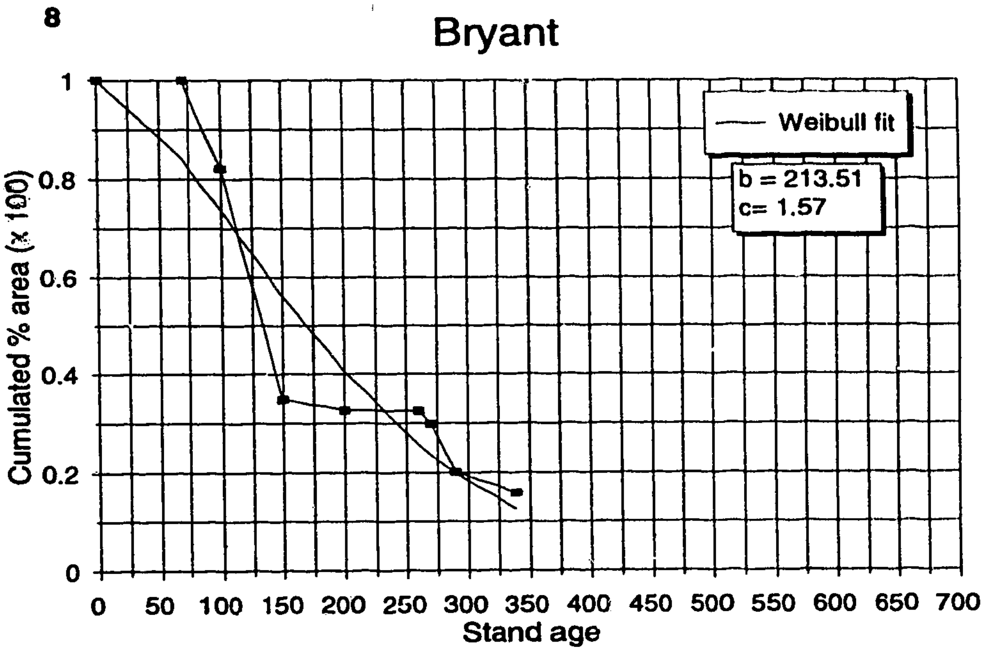
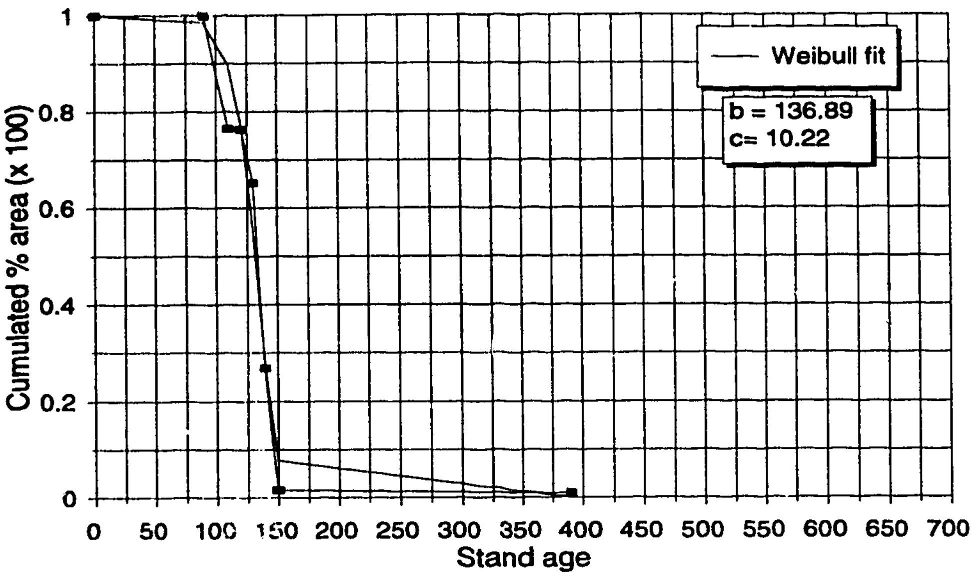
350
400
450
500
550
600
650
700
Stand age

8


Bryant
Weibull fit
b = 213.51
c= 1.57
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

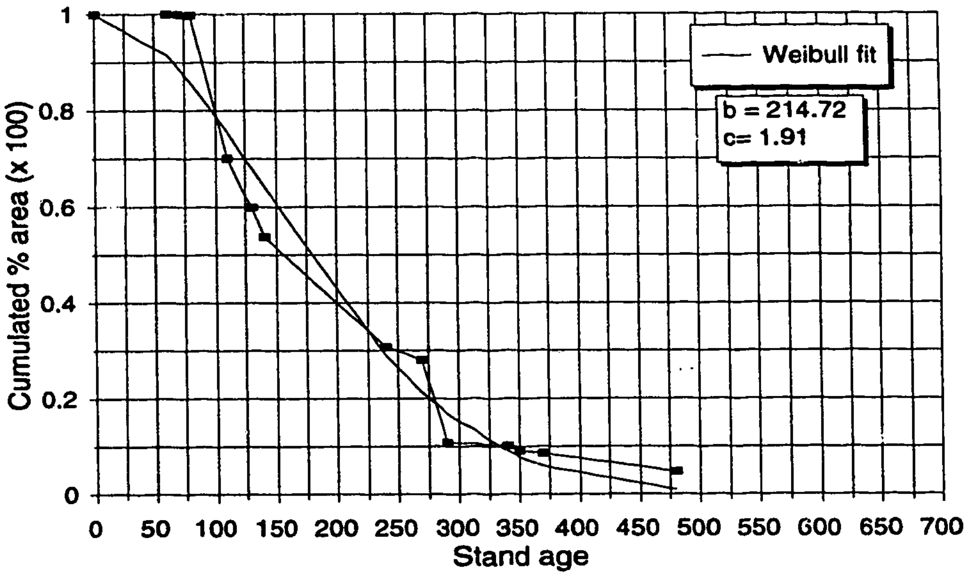
9

Carrot

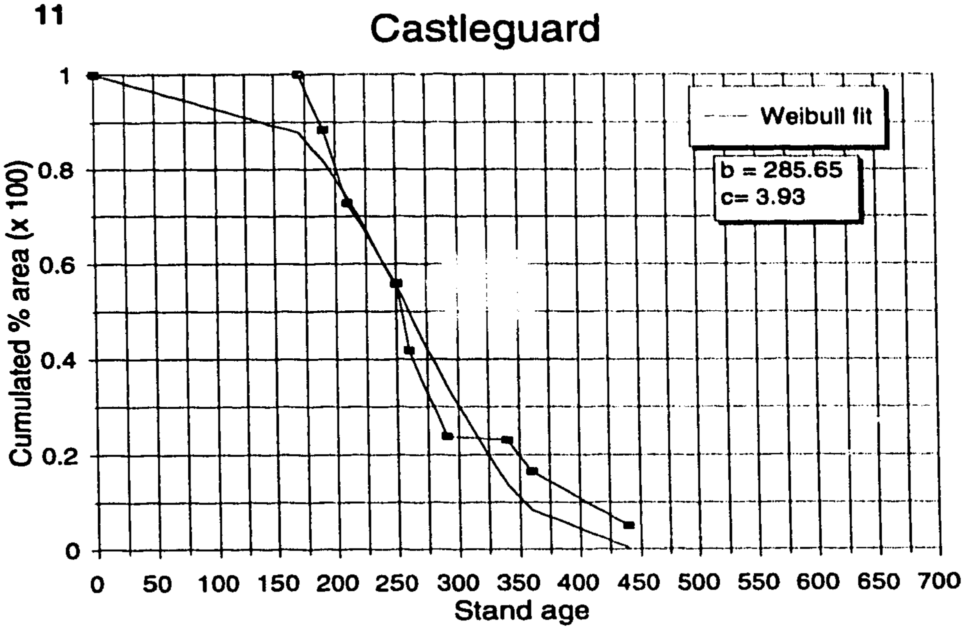


10

Cascade

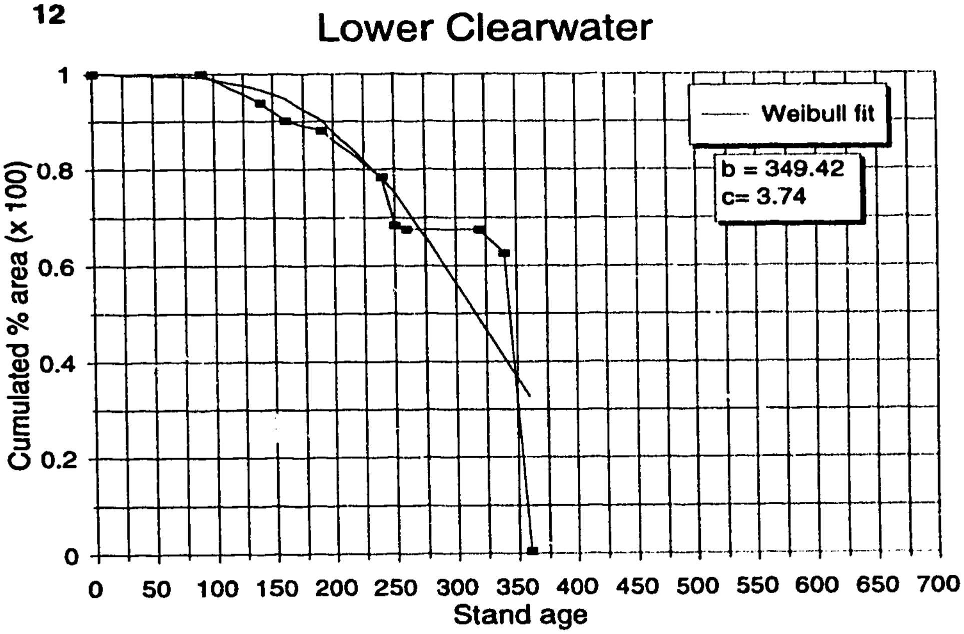


11



Castleguard
Weibull fit
b = 285.65
c= 3.93
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

12



Lower Clearwater
Weibull fit
b = 349.42
c= 3.74
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
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100
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200
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300
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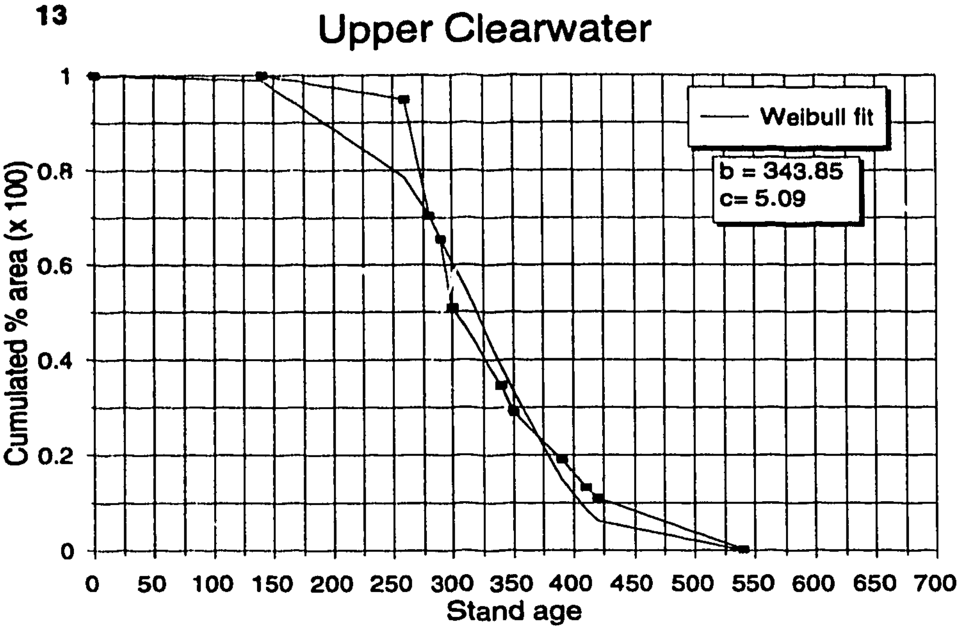
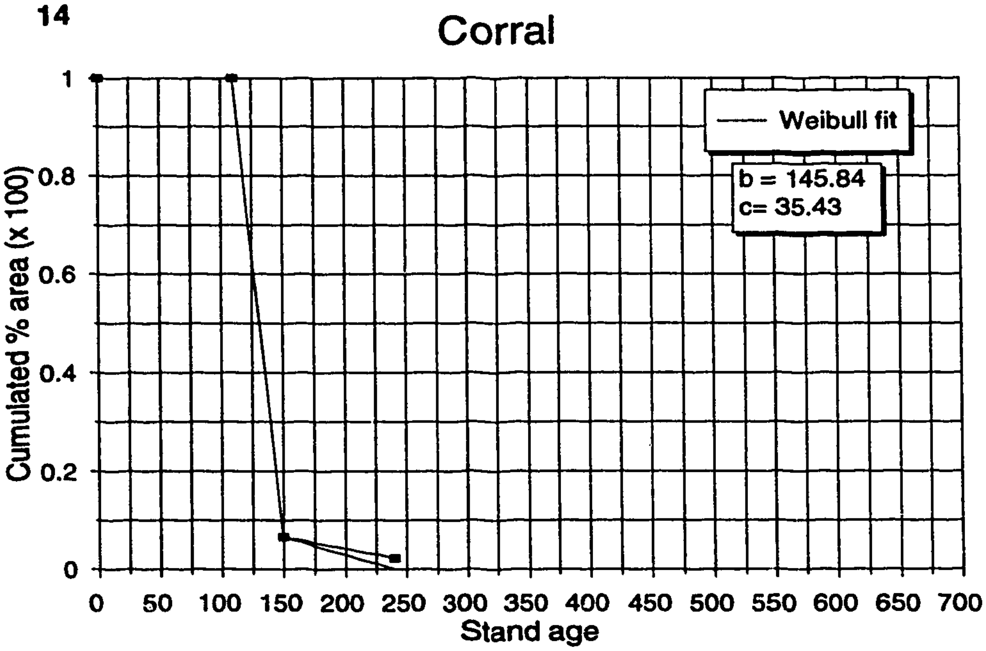
450
500
550
600
650
700
Stand age

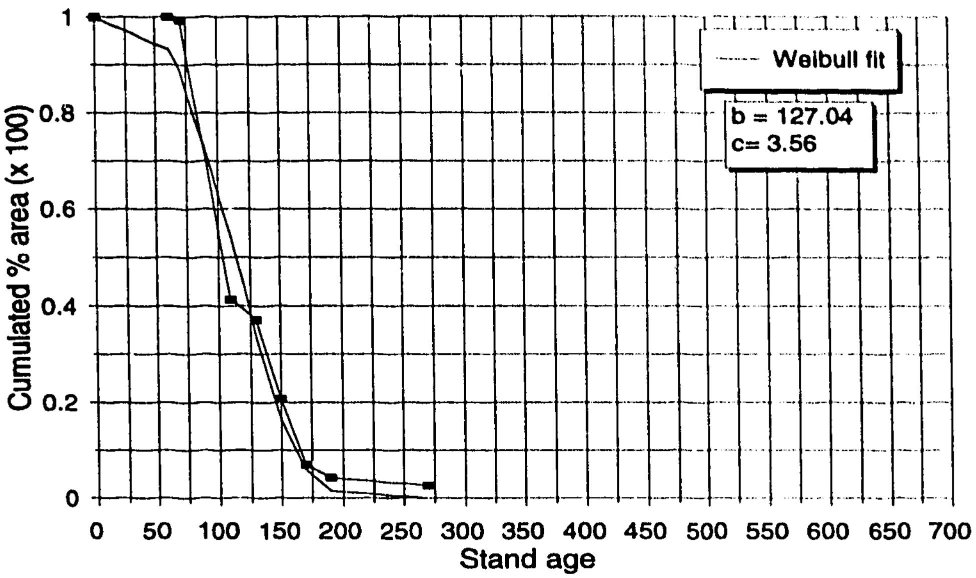
13


Upper Clearwater
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Stand age
Weibull fit
b = 343.85
c= 5.09

14

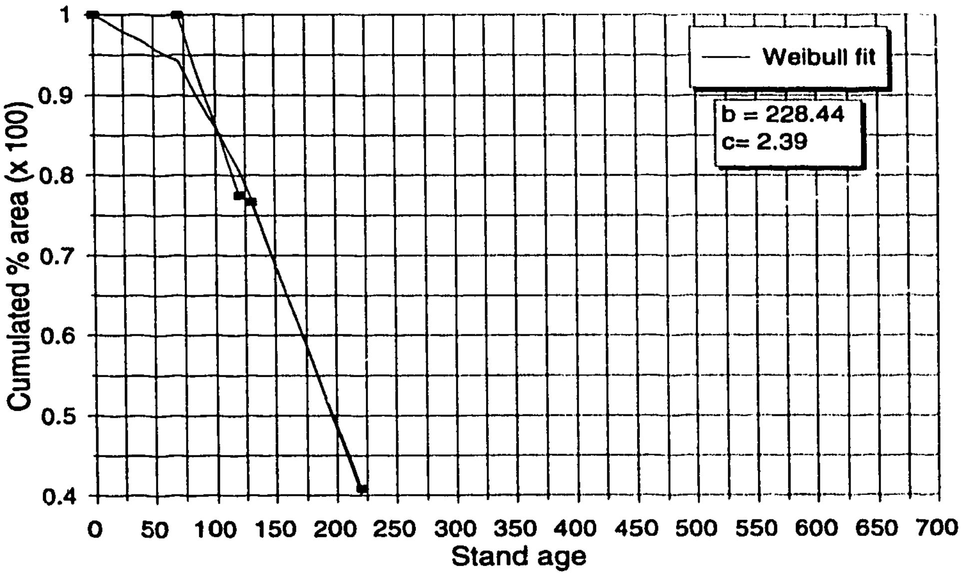

Corral
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Stand age
Weibull fit
b = 145.84
c= 35.43

15



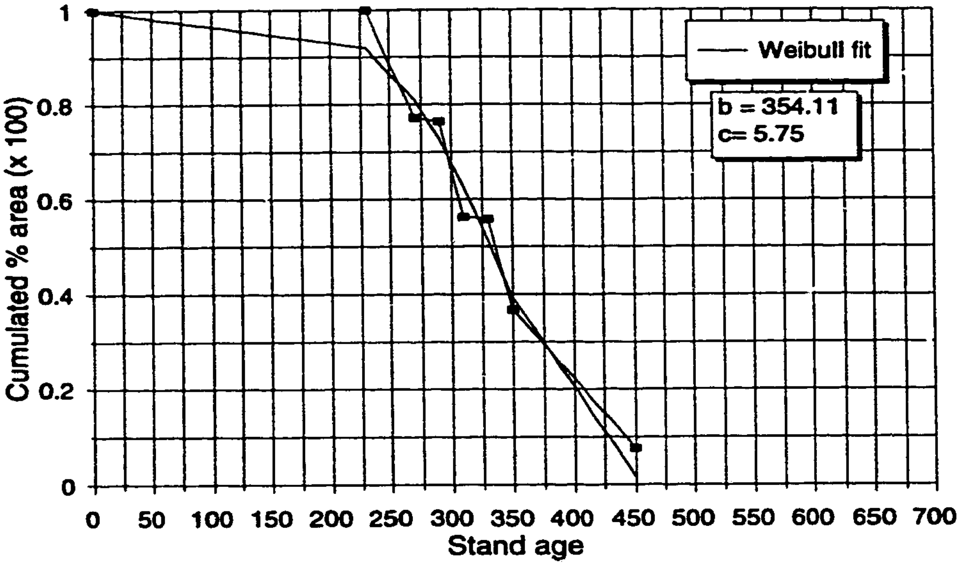
Cuthead

16

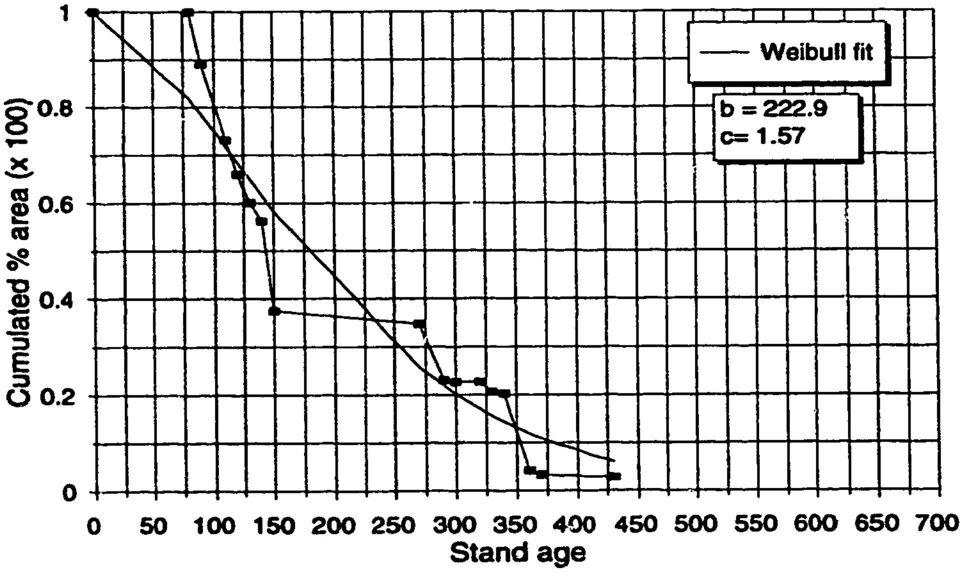


Divide

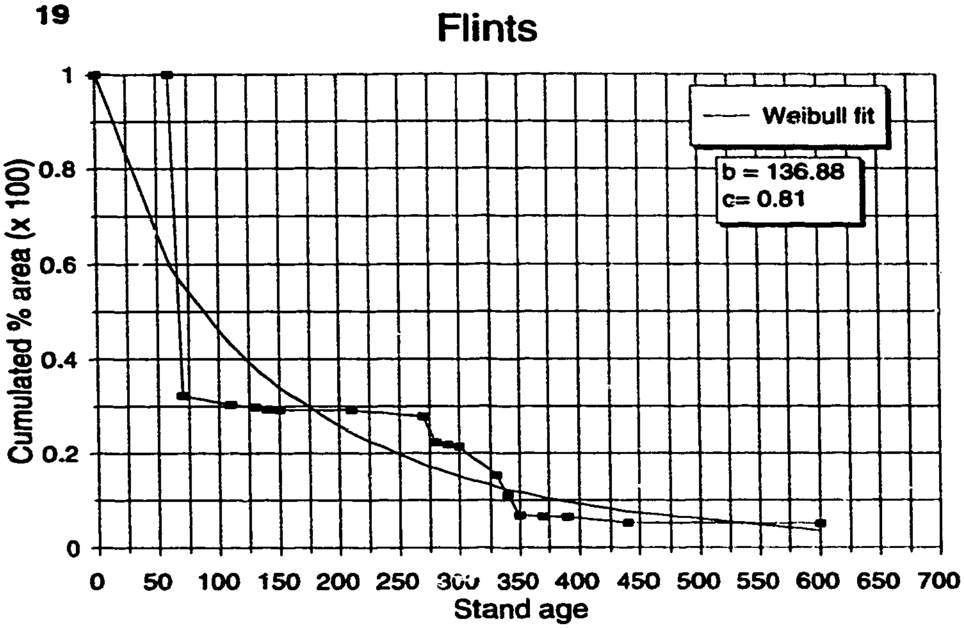
17


Dolomite

18


Dormer

19


Flints
Weibull fit
b = 136.88
c= 0.81
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
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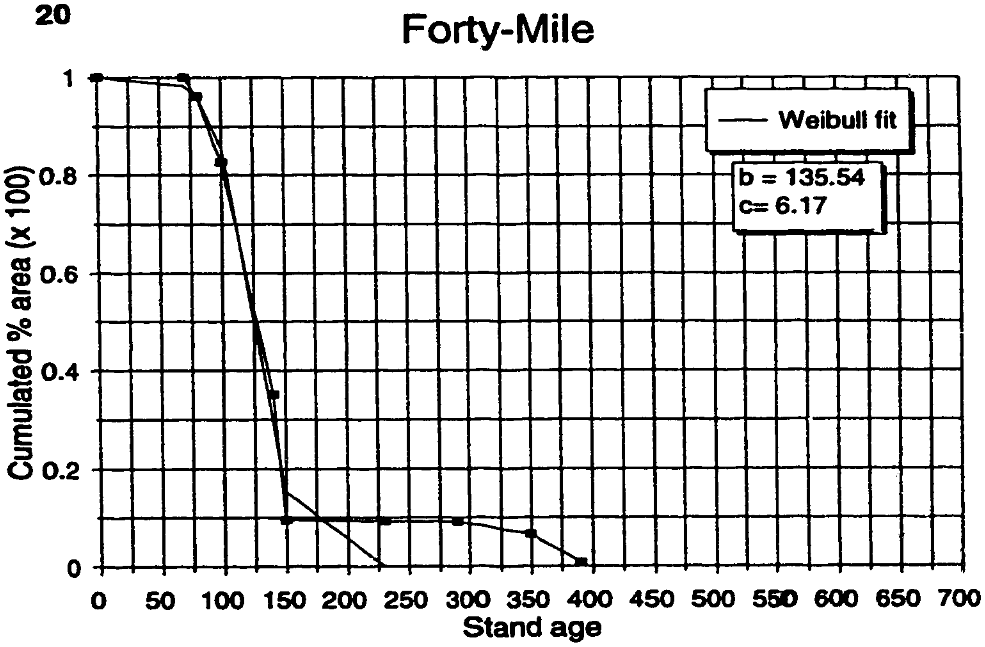
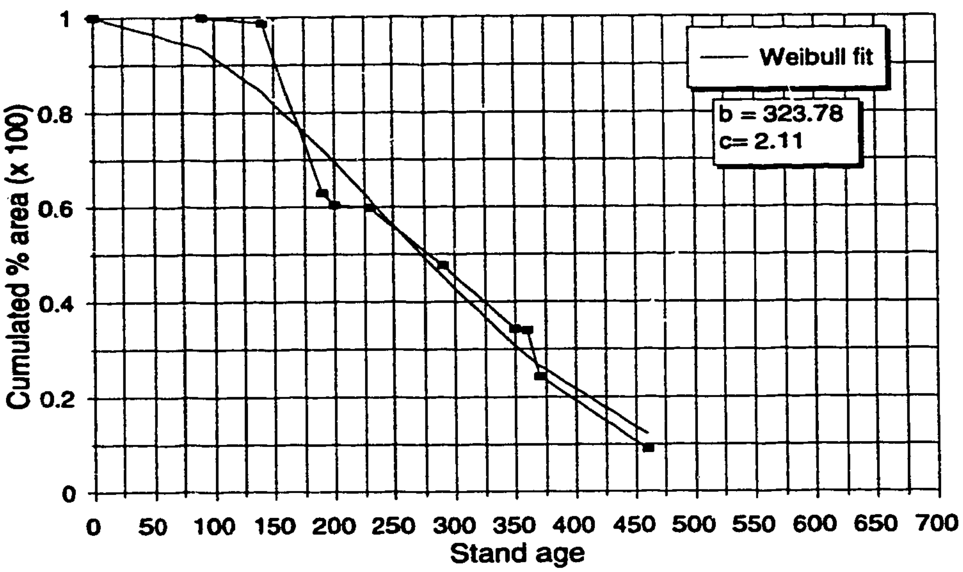
350
400
450
500
550
600
650
700
Stand age

20


Forty-Mile
Weibull fit
b = 135.54
c= 6.17
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

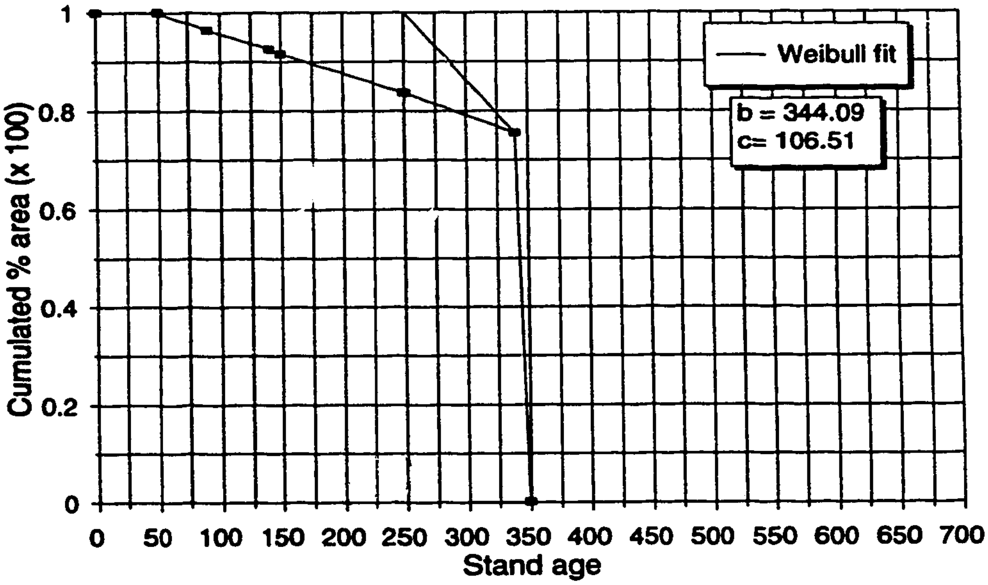
21

Healy

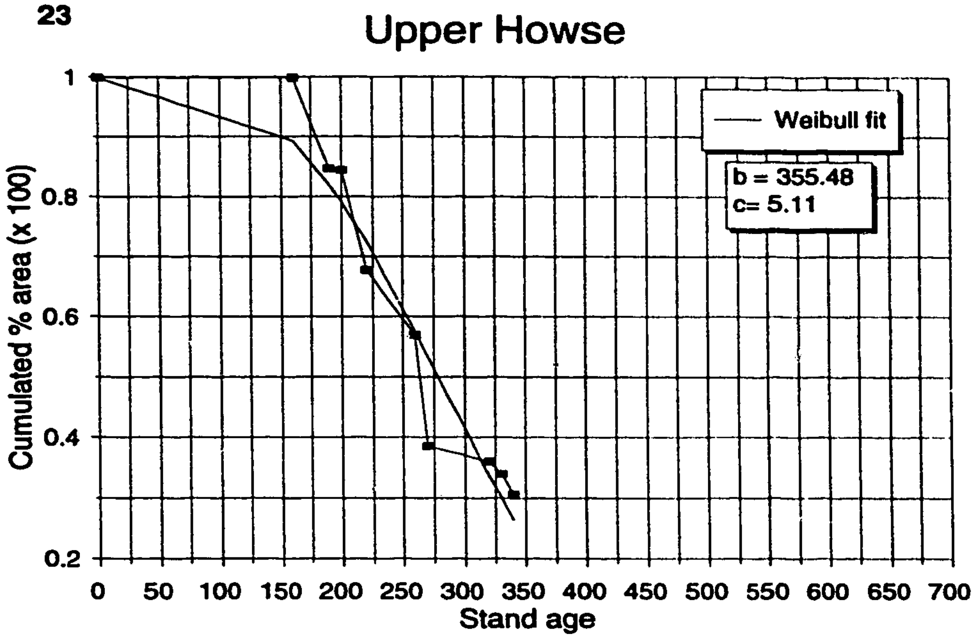


22

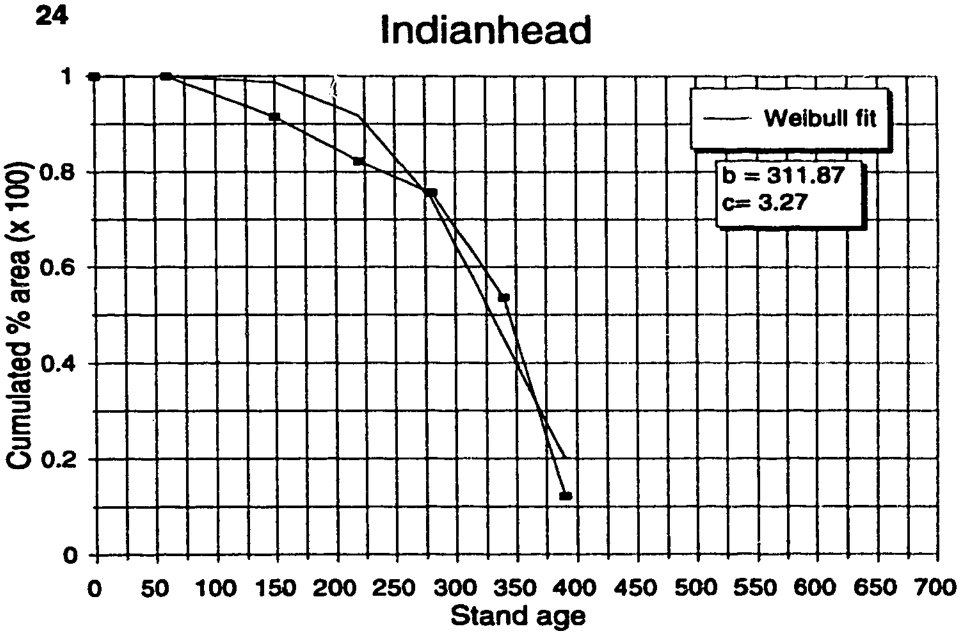
Lower Howse



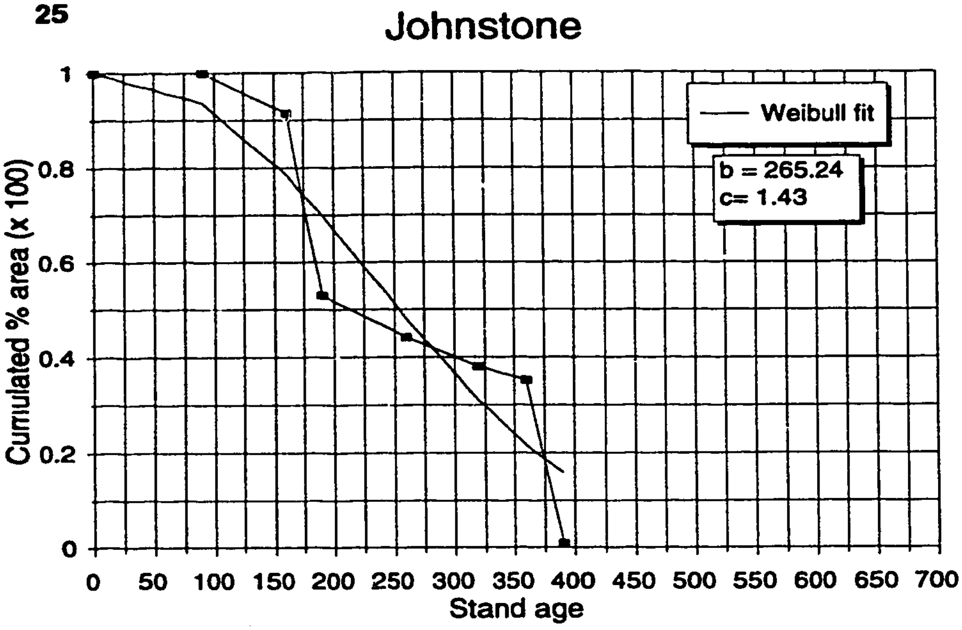
23


Upper Howse
Weibull fit
b = 355.48
c= 5.11
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

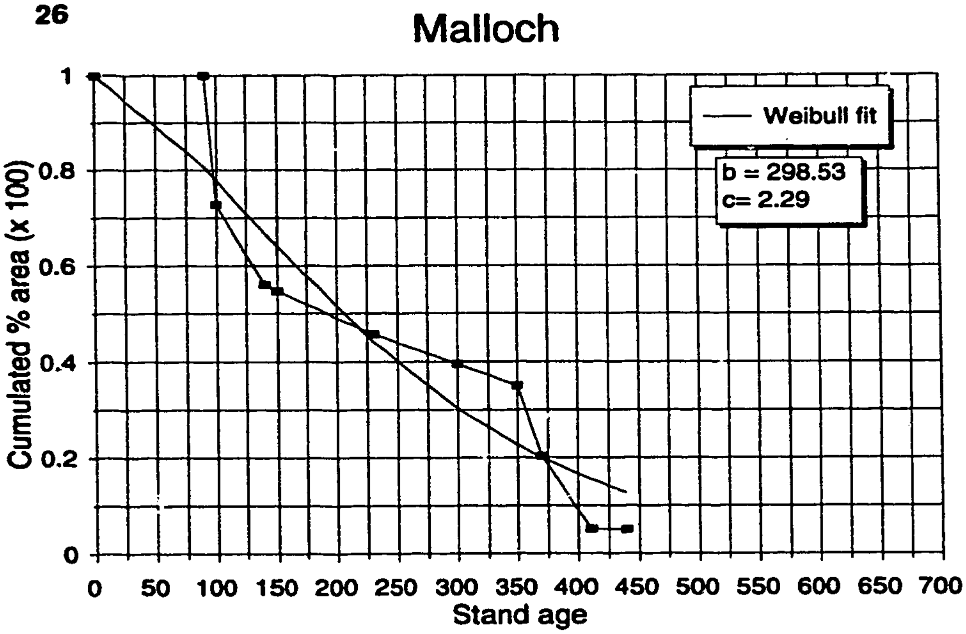
24


Indianhead
Weibull fit
b = 311.87
c= 3.27
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

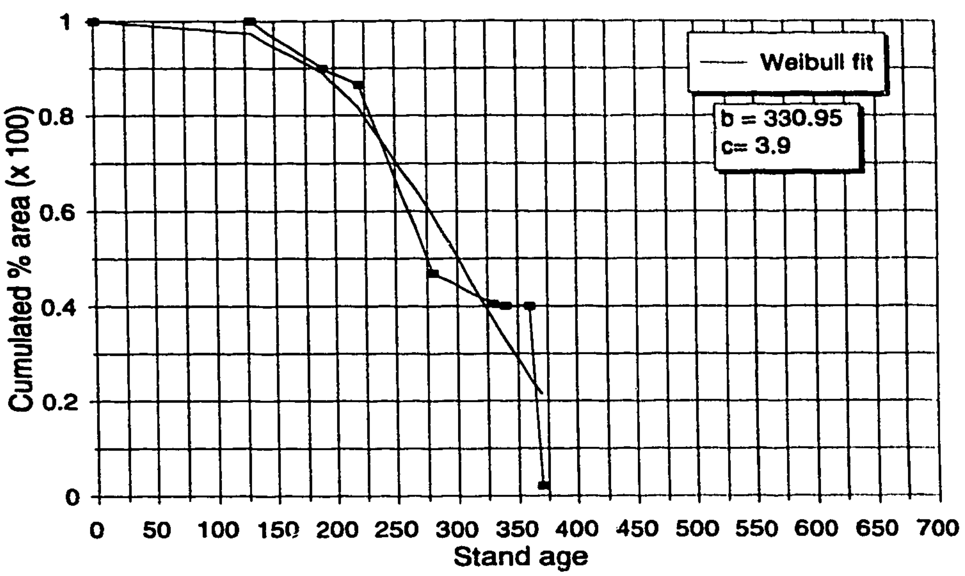
25


Johnstone
Weibull fit
b = 265.24
c= 1.43
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

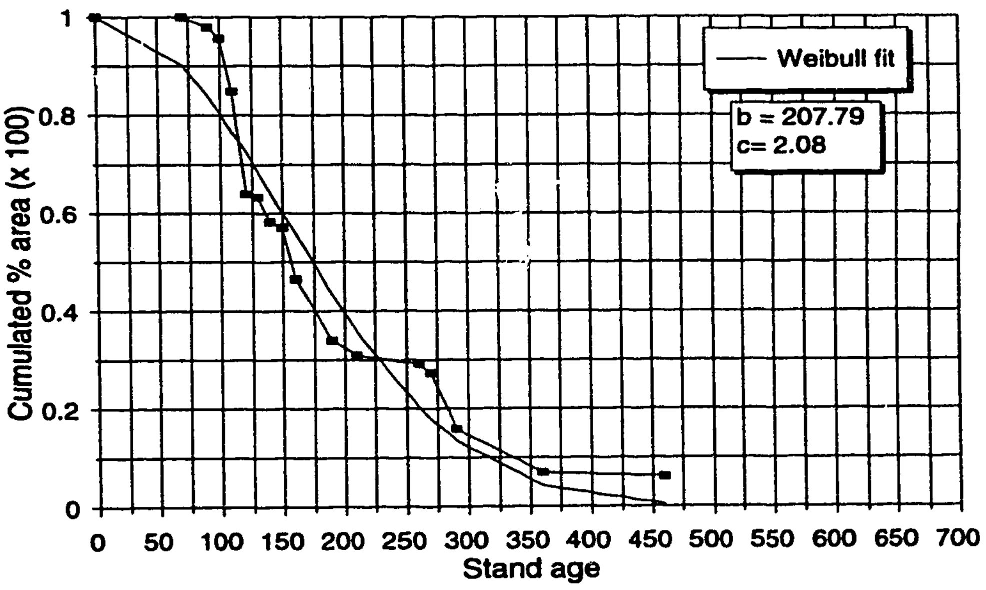
26


Malloch
Weibull fit
b = 298.53
c= 2.29
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

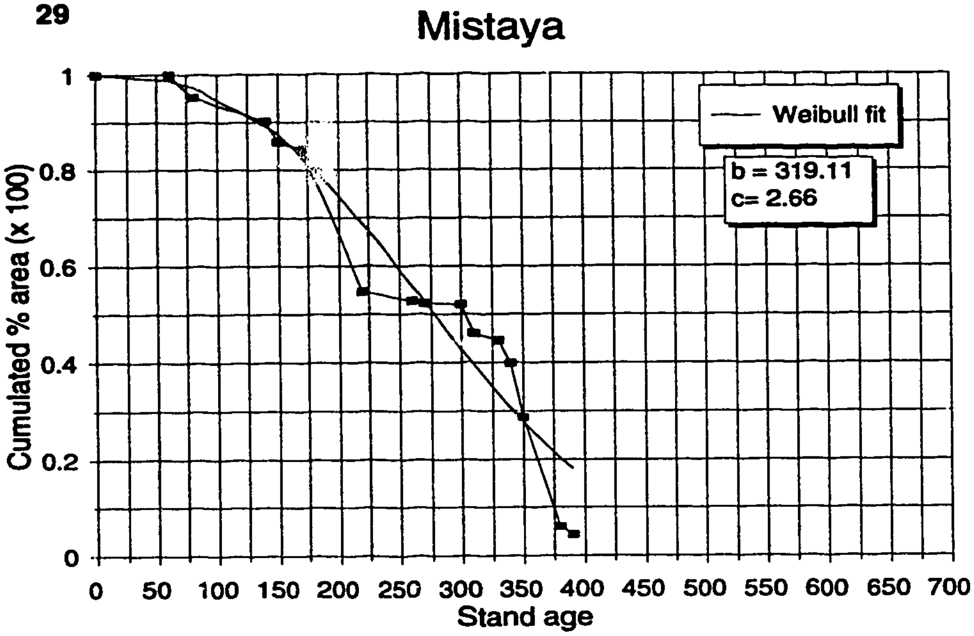
27


McConnell

28

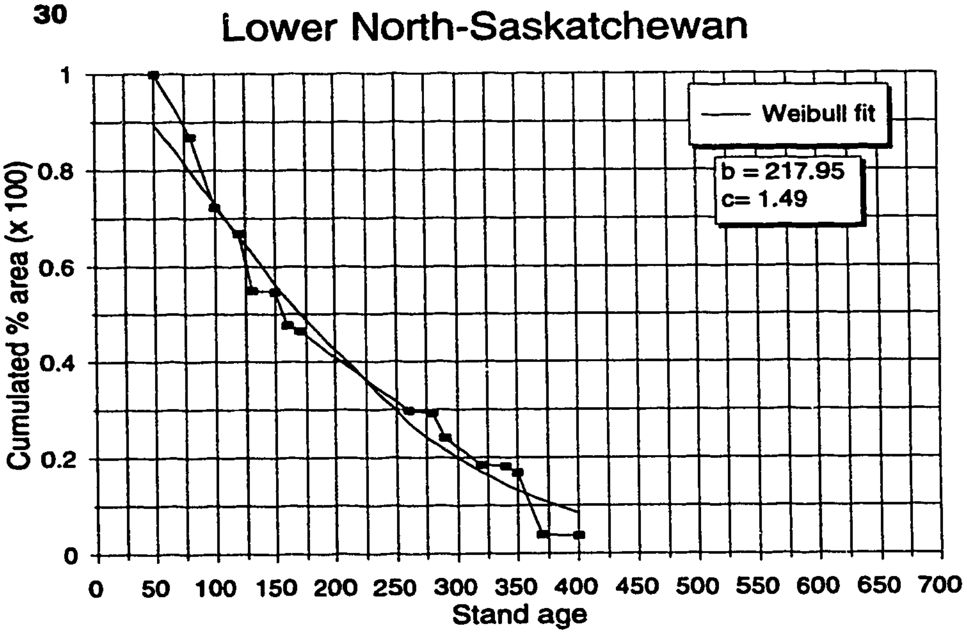

Minnewanka

29



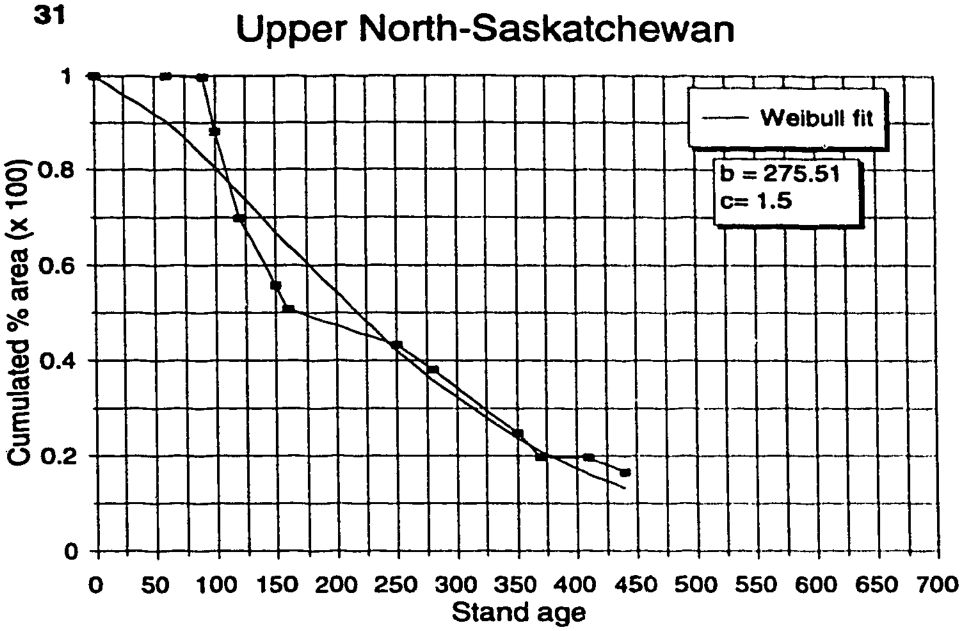
Mistaya
Weibull fit
b = 319.11
c= 2.66
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

30



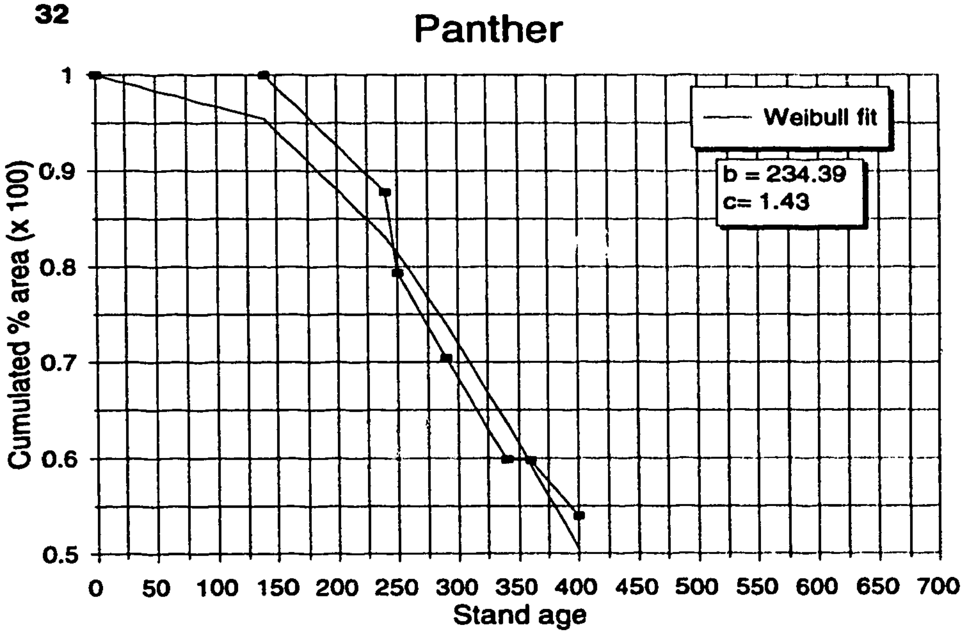
Lower North-Saskatchewan
Weibull fit
b = 217.95
c= 1.49
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

31



Upper North-Saskatchewan
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age
Weibull fit
b = 275.51
c= 1.5

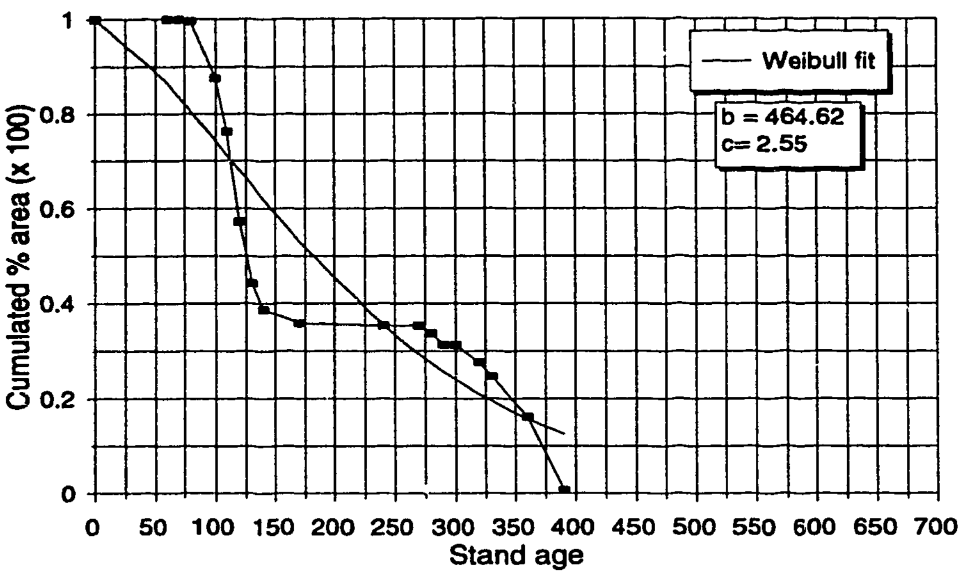
32



Panther
Cumulated % area (x 100)
1
0.9
0.8
0.7
0.6
0.5
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age
Weibull fit
b = 234.39
c= 1.43

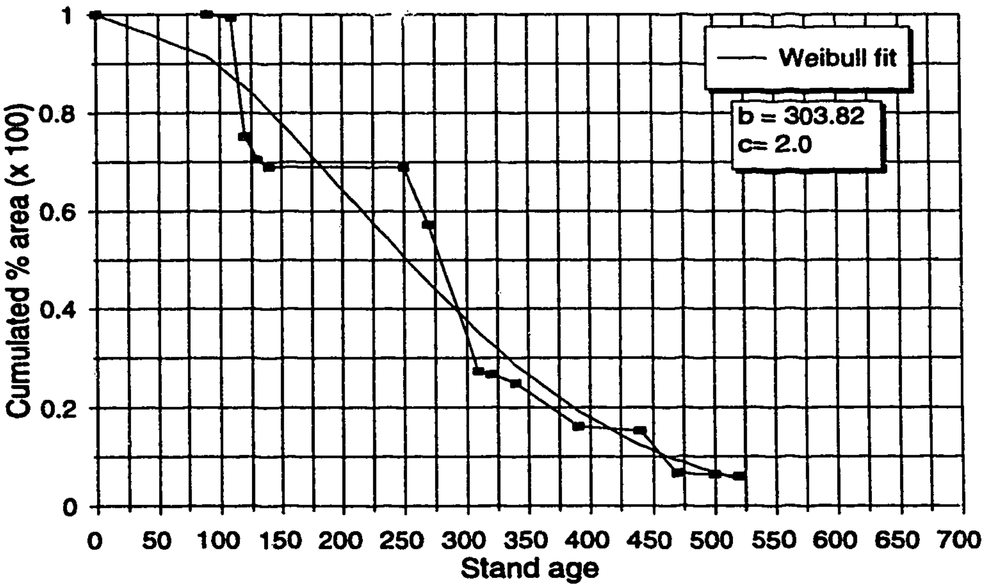
33

Peters



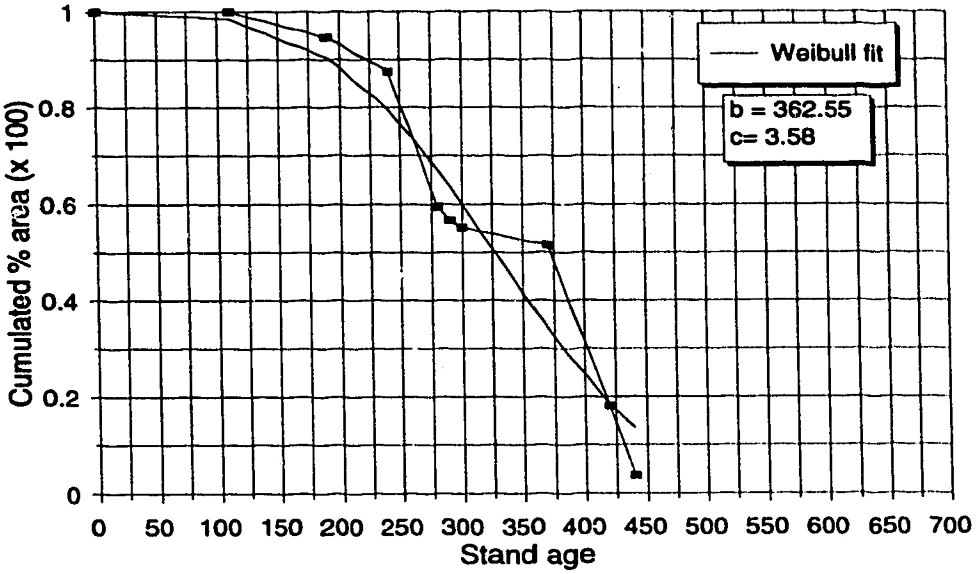
34

Pipestone



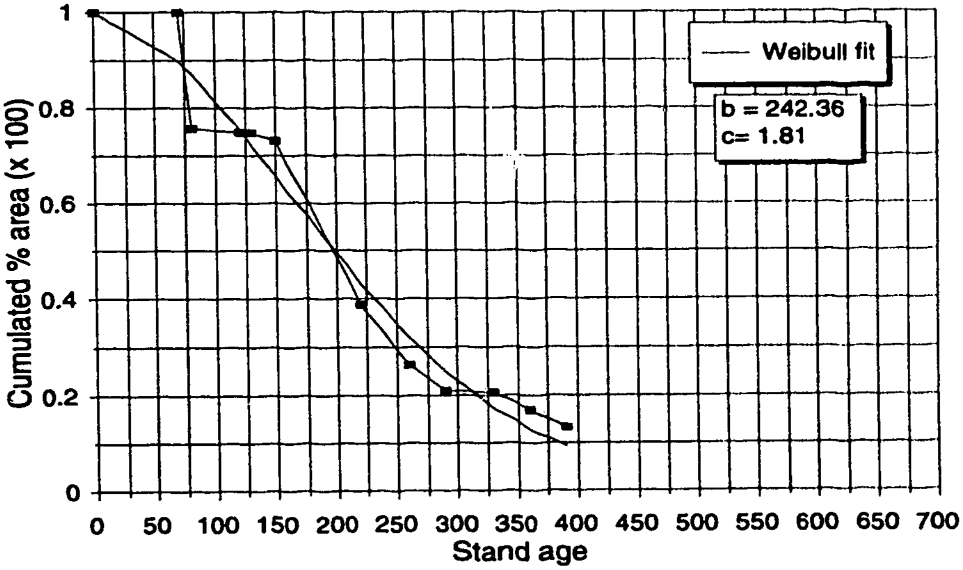
35

Redearth

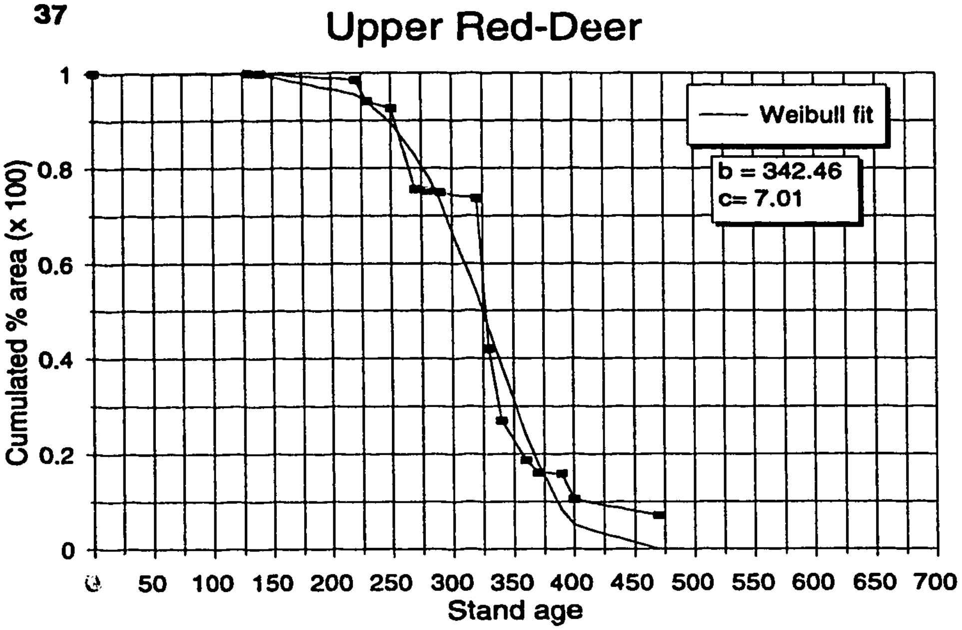


36

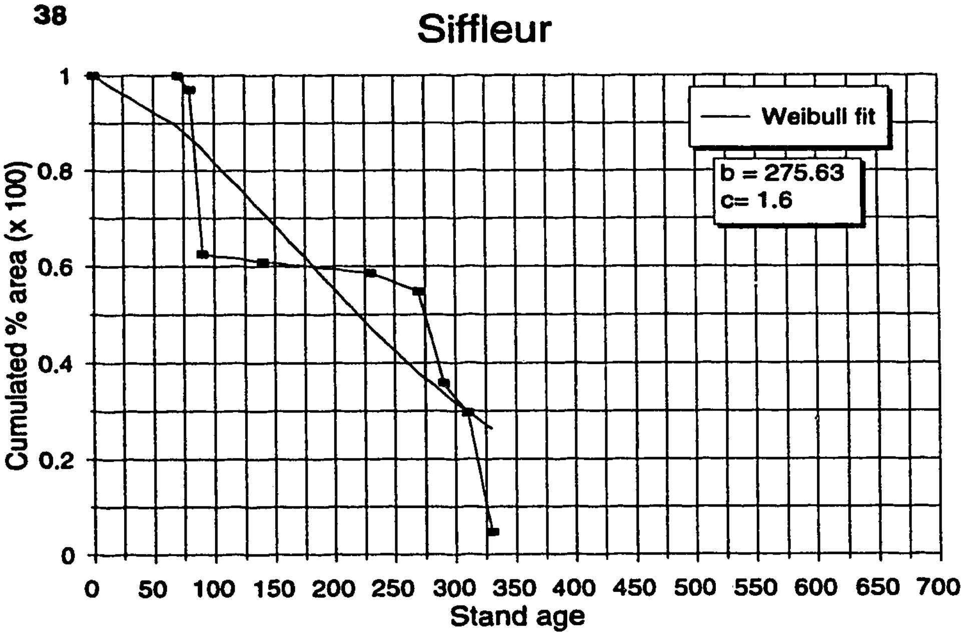
Lower Red-Deer



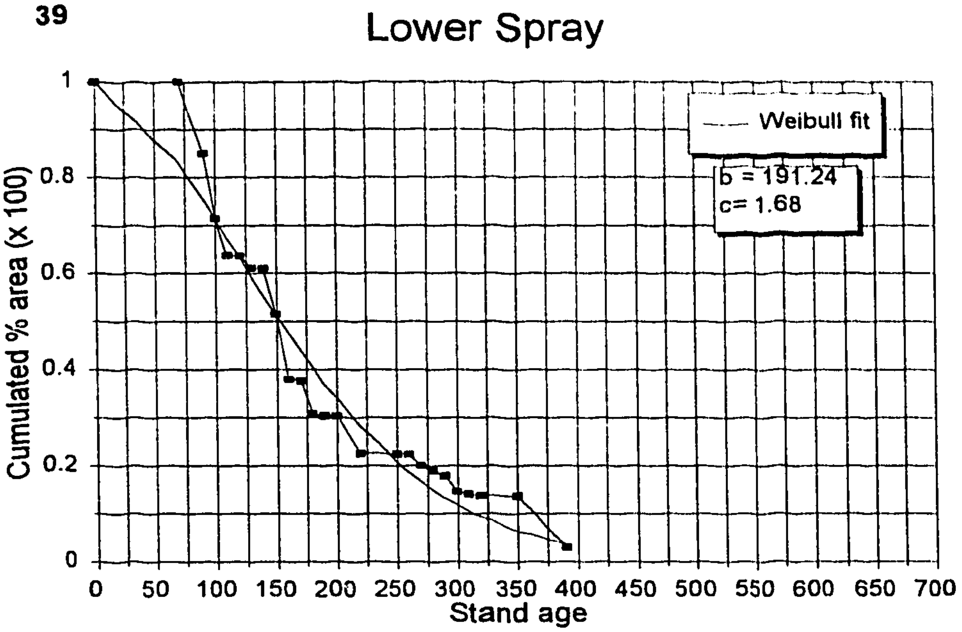
37


Upper Red-Deer
Weibull fit
b = 342.46
c= 7.01
Cumulated % area (x 100)
0
0.2
0.4
0.6
0.8
1
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Stand age

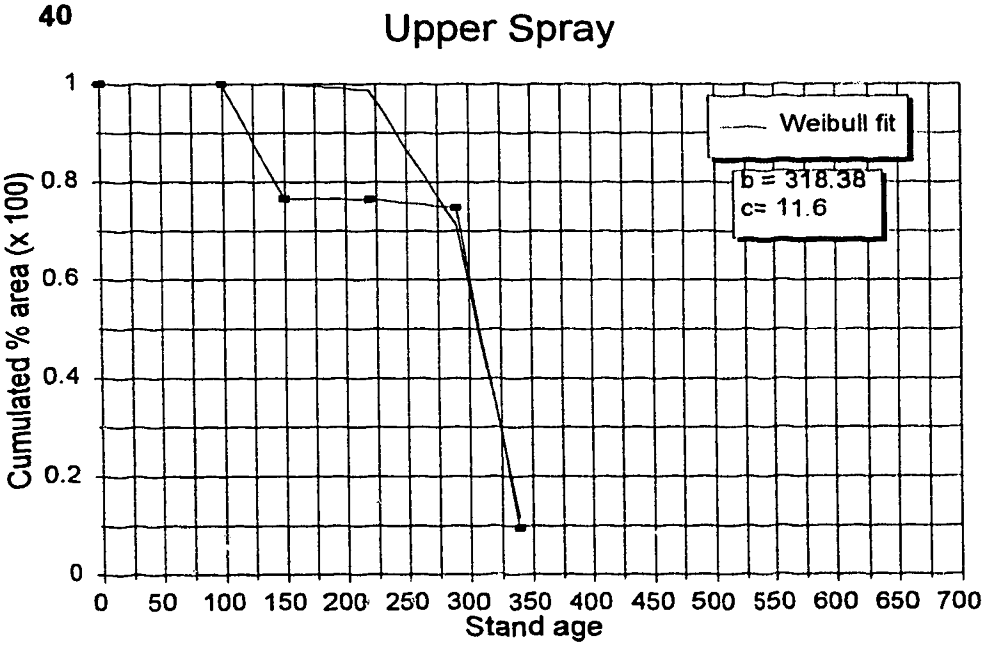
38


Siffleur
Weibull fit
b = 275.63
c= 1.6
Cumulated % area (x 100)
0
0.2
0.4
0.6
0.8
1
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Stand age

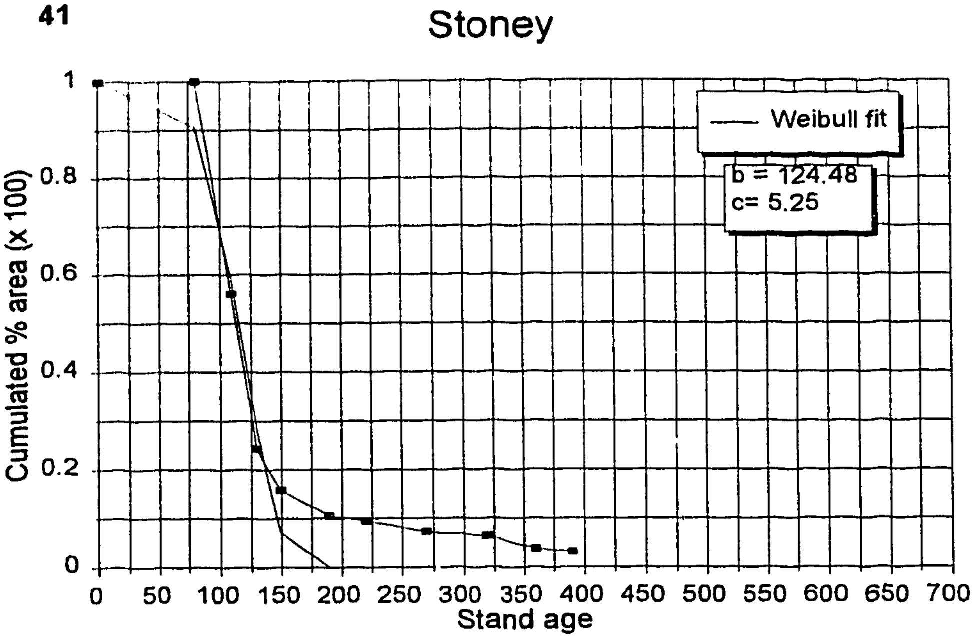
39


Lower Spray
Weibull fit
b = 191.24
c= 1.68
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

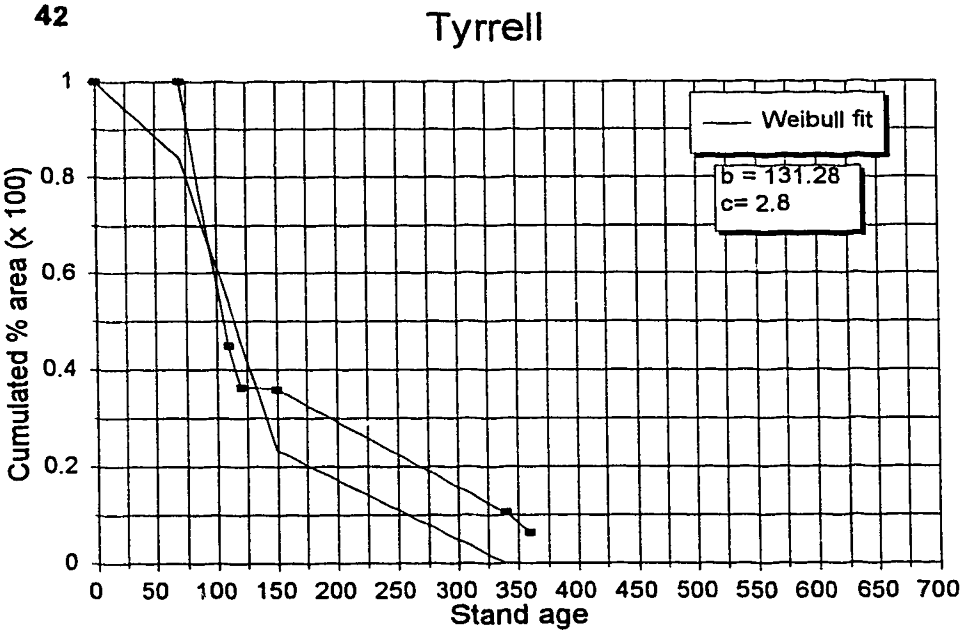
40


Upper Spray
Weibull fit
b = 318.38
c= 11.6
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

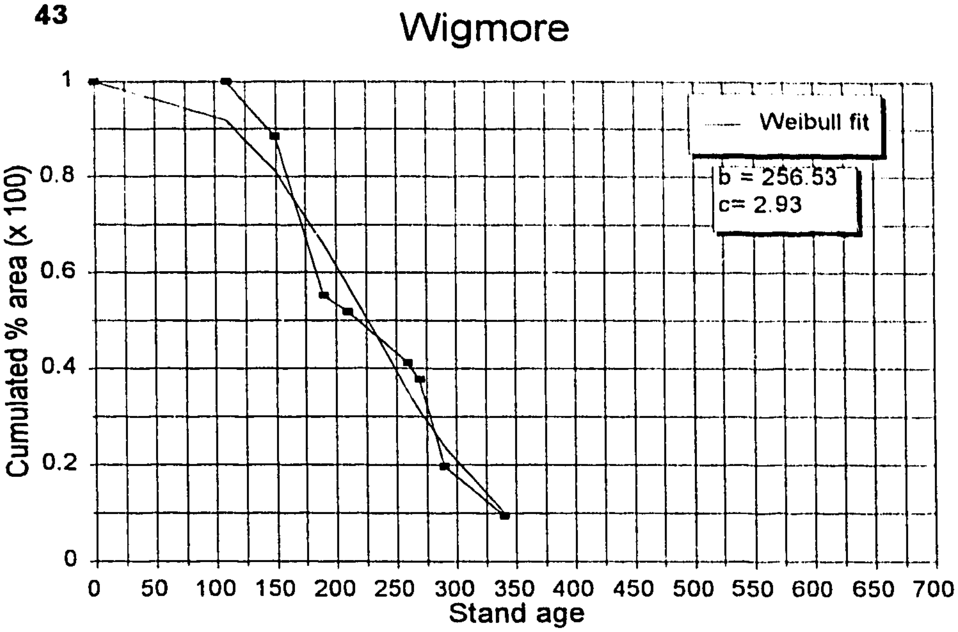
41


Stoney
Weibull fit
b = 124.48
c= 5.25
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Stand age

42


Tyrrell
Weibull fit
b = 131.28
c= 2.8
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700
Stand age

43



Wigmore
Weibull fit
b = 256.53
c= 2.93
Cumulated % area (x 100)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Stand age

APPENDIX C

Pearson's Chi square goodness-of-fit test for simulated distributions

Scenario 1

Simulation	X^2	n	$X^2_{.05,n-1}$	reject H_0
1	17.49	34	48.6	no
2	9.49	45	61.6	no
3	11.53	42	58	no
4	54.6	36	51	yes
5	18.76	42	58	no
6	51.29	34	48.6	yes
7	15.27	42	58	no
8	34.83	35	49.8	no
9	11.81	45	61.6	no
10	16.76	43	59.3	no
11	14.37	41	57	no
12	23.13	45	61.6	no
13	15.28	42	58	no
14	14.38	42	58	no
15	9.54	46	62.8	no
16	59.47	43	59.3	yes
17	16.58	44	60.4	no
18	22.31	40	55.76	no
19	14.87	38	53.4	no
20	118.88	42	58	yes
21	33.44	42	58	no
22	26.75	42	58	no
23	16.24	47	64	no
24	18.33	40	55.76	no
25	29.3	47	64	no
26	16.67	43	59.3	no
27	13.27	41	57	no
28	21.25	39	54.6	no
29	22	38	53.4	no
30	22.36	36	51	no
31	22.68	43	59.3	no
32	204.33	39	54.6	yes
33	15.12	44	60.4	no
34	33.77	35	49.8	no
35	26.26	46	62.8	no
36	11.42	45	61.6	no
37	148.2	32	46.2	yes
38	19.67	36	51	no
39	22.78	42	58	no
40	28.31	42	58	no
41	70.87	47	64	yes
42	45.64	25	38.89	yes
43	67.79	40	55.76	yes
44	6.21	39	54.6	no
45	28.01	37	52.2	no
46	55.2	42	58	no
47	21.26	31	45	no
48	9.02	42	58	no
49	15.8	34	48.6	no
50	22.42	41	57	no

Scenario 2

Simulation	X^2	n	$X^2_{.05,n-1}$	reject H_0
1	6.84	50	67.5	no
2	3.49	51	68.7	no
3	4.35	49	66.3	no
4	4.59	49	66.3	no
5	1.45	49	66.3	no
6	3.54	47	64	no
7	4.80	51	68.7	no
8	1.07	50	67.5	no
9	2.72	51	68.7	no
10	3.02	51	68.7	no
11	2.22	50	67.5	no
12	1.52	51	68.7	no
13	3.26	49	66.3	no
14	3.19	50	67.5	no
15	2.56	49	66.3	no
16	3.57	50	67.5	no
17	1.53	47	64	no
18	2.45	51	68.7	no
19	3.65	50	67.5	no
20	1.31	48	65	no
21	0.76	48	65	no
22	3.93	51	68.7	no
23	1.20	51	68.7	no
24	3.26	50	67.5	no
25	5.05	50	67.5	no
26	3.08	51	68.7	no
27	2.27	48	65	no
28	4.60	50	67.5	no
29	5.31	50	67.5	no
30	3.00	49	66.3	no
31	4.75	50	67.5	no
32	2.62	49	66.3	no
33	9.45	50	67.5	no
34	2.32	50	67.5	no
35	5.33	51	68.7	no
36	2.74	49	66.3	no
37	1.58	49	66.3	no
38	3.63	48	65	no
39	6.62	50	67.5	no
40	3.48	49	66.3	no
41	2.47	49	66.3	no
42	2.41	50	67.5	no
43	2.52	49	66.3	no
44	4.93	49	66.3	no
45	3.34	48	65	no
46	1.71	49	66.3	no
47	4.18	51	68.7	no
48	10.42	46	62.8	no
49	2.84	51	68.7	no
50	1.39	50	67.5	no

Scenario 3

Simulation	X^2	n	$X^2_{.05,n-1}$	reject H
1	8.31	47	64	no
2	5.07	50	67.5	no
3	12.27	47	64	no
4	9.12	51	68.7	no
5	11.48	49	66.3	no
6	6.34	49	66.3	no
7	3.88	50	67.5	no
8	36.34	51	68.7	no
9	16.23	47	64	no
10	19.33	50	67.5	no
11	9.37	50	67.5	no
12	6.71	46	62.8	no
13	18.42	49	66.3	no
14	5.81	50	67.5	no
15	38.37	48	65	no
16	6.60	50	67.5	no
17	8.99	51	68.7	no
18	6.00	47	64	no
19	3.85	51	68.7	no
20	46.94	49	66.3	no
21	14.17	51	68.7	no
22	7.60	51	68.7	no
23	4.44	47	64	no
24	8.54	47	64	no
25	11.63	48	65	no

APPENDIX D

Magnitude of variation of simulated survivorship patterns

Scenario 1: Magnitude of variation for 15 cumulated age-class distributions (survivorship), and burn area by age-classes.

		Cumulated			Area	
Age-classes	Mean	Std dev.	Coef. variation	Mean	Std err.	[illegible]
10	1.0000	0.0000	0.0000	1509.87	1106.63	[illegible]
20	0.9597	0.0306	3.1847	2139.87	1740.05	[illegible]
30	0.9021	0.0608	6.7453	1356.27	2157.63	[illegible]
40	0.8603	0.0788	9.1652	2098.00	1747.97	[illegible]
50	0.7959	0.0993	12.4743	1476.27	2313.11	[illegible]
60	0.7579	0.1006	13.2730	1393.27	1879.76	[illegible]
70	0.7229	0.0864	11.9569	2225.27	2388.64	[illegible]
80	0.6659	0.0862	12.9462	978.80	1034.12	[illegible]
90	0.6366	0.0914	14.3539	1123.40	1111.04	[illegible]
100	0.6054	0.0888	14.6624	1132.20	1820.27	[illegible]
110	0.5794	0.0819	14.1286	810.20	755.66	[illegible]
120	0.5576	0.0850	15.2358	847.40	553.10	[illegible]
130	0.5354	0.0864	16.1438	725.00	870.84	[illegible]
140	0.5166	0.0862	16.6793	435.13	322.98	74.23
150	0.5037	0.0866	17.1960	959.87	794.45	82.77
160	0.4769	0.0949	19.8921	1038.53	1662.00	160.03
170	0.4517	0.0883	19.5379	943.93	1080.40	114.46
180	0.4291	0.0878	20.4536	1036.53	987.59	95.28
190	0.4012	0.0880	21.9464	647.07	1043.79	161.31
200	0.3812	0.1022	26.8042	603.60	818.79	135.65
210	0.3676	0.0978	26.6068	670.00	1124.75	167.87
220	0.3497	0.0928	26.5378	563.53	614.66	109.07
230	0.3337	0.0877	26.2747	877.00	1016.64	115.92
240	0.3105	0.0820	26.4009	543.40	937.45	172.52
250	0.2983	0.0796	26.6756	706.80	929.30	131.48
260	0.2795	0.0758	27.1286	1053.20	1266.24	120.23
270	0.2491	0.0680	27.2885	570.33	985.73	172.83
280	0.2327	0.0624	26.8108	500.53	955.42	190.88
290	0.2213	0.0602	27.1865	608.40	611.96	100.59
300	0.2066	0.0578	27.9614	543.13	611.71	112.63
310	0.1908	0.0588	30.8115	305.13	903.14	295.98
320	0.1816	0.0607	33.4256	200.80	201.13	100.16
330	0.1758	0.0601	34.1788	258.47	372.35	144.06
340	0.1691	0.0590	34.9169	249.60	515.99	206.73
350	0.1638	0.0561	34.2742	431.73	578.06	133.89
360	0.1528	0.0492	32.1862	110.47	198.39	179.59
370	0.1501	0.0494	32.9341	417.93	701.06	167.74
380	0.1405	0.0447	31.7855	345.27	862.72	249.87
390	0.1337	0.0421	31.4633	119.13	287.20	241.07
400	0.1313	0.0421	32.0614	134.67	127.61	94.76
410	0.1278	0.0400	31.2945	269.60	526.32	195.22
420	0.1214	0.0382	31.4874	109.33	329.31	301.21
430	0.1183	0.0360	30.3958	157.73	333.91	211.70
440	0.1134	0.0388	34.2545	264.47	472.26	178.57
450	0.1058	0.0415	39.2268	298.40	314.65	105.45
460	0.0971	0.0375	38.6072	266.67	697.89	261.71
470	0.0888	0.0352	39.6334	176.93	328.67	185.76
480	0.0849	0.0332	39.0890	324.40	426.84	131.58
490	0.0768	0.0291	37.8705	226.80	329.39	145.23
500	0.0703	0.0268	38.0765	29.33	83.22	283.74
510	0.0694	0.0262	37.8062	2817.13	2007.59	71.26

Scenario 2: Magnitude of variation for 15 cumulated age-class distributions (survivorship), and burn area by age-classes.

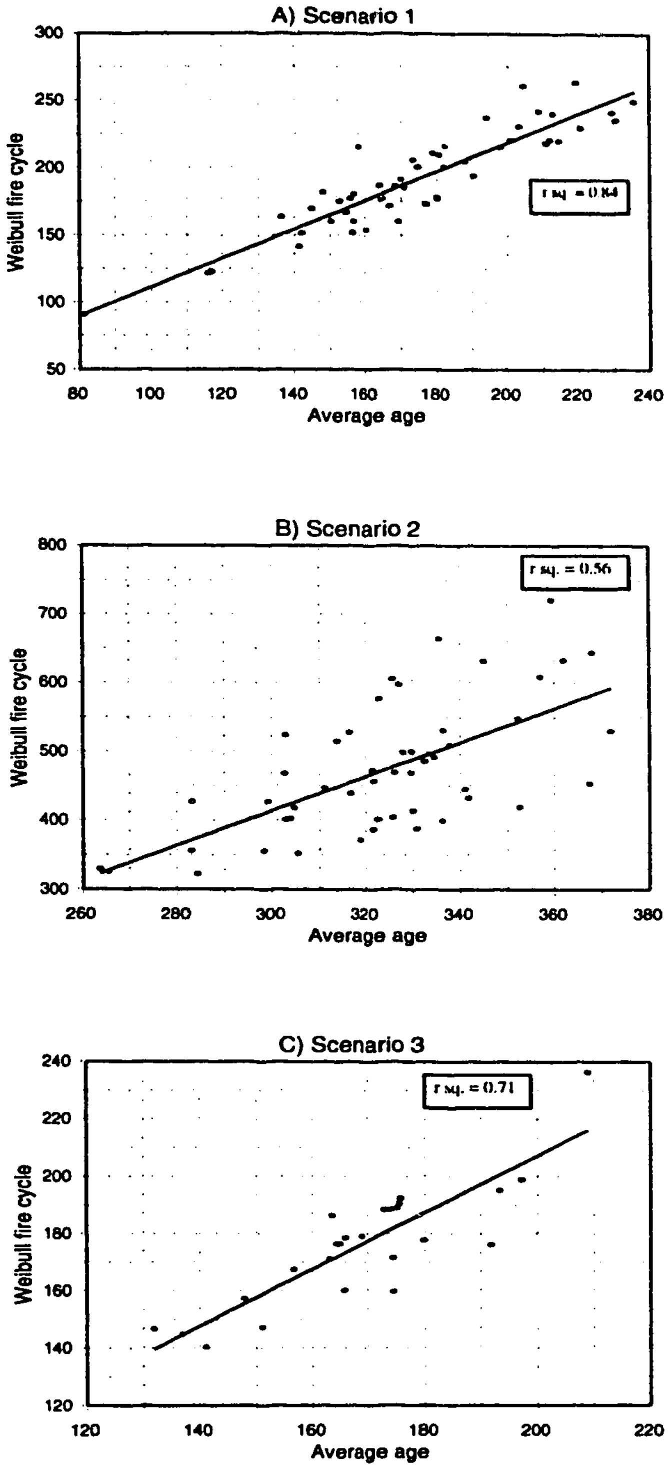
	Cumulated			Area		
[illegible]	Mean	Std dev.	[illegible]	Mean	Std err.	[illegible]
10	1.0000	0.0000	0.0000	2928.40	1870.24	[illegible]
20	0.9852	0.0104	[illegible]	3800.40	2220.92	[illegible]
30	0.9647	0.0142	[illegible]	3330.13	2962.21	[illegible]
40	0.9463	0.0234	[illegible]	4056.93	3656.17	[illegible]
50	0.9263	0.0312	[illegible]	2828.93	3527.46	[illegible]
60	0.9094	0.0360	[illegible]	4602.93	2460.52	[illegible]
70	0.8840	0.0447	[illegible]	3766.93	1907.29	[illegible]
80	0.8660	0.0395	[illegible]	3811.27	2266.94	[illegible]
90	0.8446	0.0411	[illegible]	2698.33	2895.89	107.32
100	0.8257	0.0496	6.0122	3189.53	2333.92	[illegible]
110	0.8093	0.0500	6.1810	3281.27	2940.75	[illegible]
120	0.7921	0.0511	[illegible]	3077.00	1929.98	62.72
130	0.7751	0.0548	[illegible]	3995.93	2758.26	69.03
140	0.7569	0.0520	6.8746	2938.27	1764.59	60.06
150	0.7428	0.0527	7.1006	2894.13	3117.43	107.72
160	0.7298	0.0495	6.7853	2628.93	2674.30	101.73
170	0.7175	0.0480	6.6952	2427.33	3053.59	125.80
180	0.7063	0.0495	7.0066	2019.67	1544.05	76.45
190	0.6958	0.0480	6.8948	2784.53	2191.90	78.72
200	0.6815	0.0551	8.0842	2673.67	3293.74	123.19
210	0.6669	0.0561	8.4132	2248.53	1604.40	71.35
220	0.6548	0.0588	8.9839	2375.53	2106.94	88.69
230	0.6412	0.0582	9.0740	3013.13	2219.56	73.66
240	0.6265	0.0584	9.3254	2747.00	2944.79	107.20
250	0.6136	0.0634	10.3323	2098.47	1165.93	55.56
260	0.6018	0.0651	10.8117	2026.07	1409.22	69.55
270	0.5905	0.0640	10.8344	2239.93	1821.56	81.32
280	0.5804	0.0658	11.3315	1764.87	2184.95	123.80
290	0.5708	0.0637	11.1615	2245.20	2267.35	100.99
300	0.5588	0.0610	10.9237	3096.27	2579.62	83.31
310	0.5453	0.0664	12.1686	1755.13	1174.17	66.90
320	0.5345	0.0685	12.8069	2072.53	2340.42	112.93
330	0.5255	0.0646	12.2859	1511.67	1098.54	72.67
340	0.5183	0.0649	12.5213	1683.47	2304.56	136.89
350	0.5085	0.0655	12.8861	2082.00	1645.36	79.03
360	0.4982	0.0637	12.7900	1936.33	1033.10	53.35
370	0.4879	0.0652	13.3717	2104.33	2067.57	98.25
380	0.4766	0.0633	13.2836	2040.13	1593.05	78.09
390	0.4654	0.0634	13.6159	2040.33	1247.48	61.14
400	0.4549	0.0610	13.4096	2193.93	2506.02	114.23
410	0.4421	0.0570	12.8987	1732.60	1383.52	79.85
420	0.4343	0.0560	12.8857	1722.27	1299.80	75.47
430	0.4238	0.0588	13.8815	2066.93	1600.56	77.44
440	0.4135	0.0575	13.9119	2507.07	2614.67	104.29
450	0.4005	0.0553	13.8019	1593.53	1388.42	87.13
460	0.3929	0.0568	14.4459	2249.53	3467.29	154.13
470	0.3817	0.0506	13.2657	1446.60	1621.46	112.09
480	0.3739	0.0519	13.8875	1992.47	1251.64	62.82
490	0.3639	0.0507	13.9247	1260.93	1237.31	98.13
500	0.3564	0.0492	13.8010	1147.93	1020.59	88.91
510	0.3498	0.0495	14.1409	69322.47	24038.25	34.68

Scenario 3 Magnitude of variation for 15 cumulated age-class distributions (survivorship), and burn area by age-classes.

	Cumulated			Area		
Age-class	Mean	Std dev.	Coef of variation	Mean	Std err.	% of variation
10	1.0000	0.0000	0.0000	9035.60	6265.75	69.3451
20	0.9457	0.0390	4.1198	9756.00	7619.04	78.0959
30	0.8871	0.0670	7.5575	8798.87	4785.32	54.3857
40	0.8343	0.0724	8.6803	6446.00	3889.50	60.3398
50	0.7955	0.0833	10.4699	6935.93	4997.14	72.0473
60	0.7539	0.0683	9.0587	6362.33	4848.31	76.2034
70	0.7156	0.0712	9.9432	7845.13	5203.90	66.3328
80	0.6685	0.0715	10.6891	7342.67	4845.18	65.9866
90	0.6244	0.0765	12.2530	6246.20	3902.96	62.4854
100	0.5869	0.0830	14.1467	7097.80	4370.38	61.5737
110	0.5442	0.0825	15.1510	6043.73	4674.58	77.3458
120	0.5079	0.0761	14.9847	4700.87	3224.87	68.6016
130	0.4797	0.0681	14.1990	3658.07	1899.86	51.9362
140	0.4577	0.0650	14.1925	4389.00	3220.52	73.3771
150	0.4314	0.0614	14.2338	4179.00	2891.18	69.1834
160	0.4063	0.0548	13.4992	5051.47	2835.47	56.1317
170	0.3759	0.0595	15.8363	3568.87	2014.40	56.4437
180	0.3545	0.0584	16.4666	2511.00	2539.92	101.1516
190	0.3394	0.0573	16.8808	2727.60	2732.05	100.1633
200	0.3230	0.0551	17.0679	2176.87	1668.96	76.6680
210	0.3099	0.0520	16.7748	3083.27	1626.23	52.7437
220	0.2914	0.0499	17.1364	2105.47	1480.08	70.2969
230	0.2788	0.0534	19.1585	3161.47	2426.79	76.7615
240	0.2598	0.0591	22.7508	3057.67	3131.49	102.4145
250	0.2414	0.0555	22.9958	1998.53	1311.76	65.6360
260	0.2294	0.0536	23.3795	2076.93	1462.97	70.4391
270	0.2169	0.0522	24.0540	1904.53	1698.19	89.1657
280	0.2055	0.0462	22.4783	2233.27	1692.66	75.7930
290	0.1921	0.0389	20.2472	1899.87	1806.60	95.0909
300	0.1806	0.0395	21.8880	2013.60	1271.31	63.1362
310	0.1685	0.0433	25.7179	1914.67	1270.85	66.3747
320	0.1570	0.0445	28.3134	1647.20	1529.78	92.8715
330	0.1471	0.0412	28.0179	1244.80	943.13	75.7653
340	0.1397	0.0400	28.6362	871.07	938.57	107.7500
350	0.1344	0.0381	28.3096	1157.20	1146.01	99.0333
360	0.1275	0.0360	28.2485	1388.33	1323.71	95.3455
370	0.1191	0.0326	27.3799	614.93	680.41	110.6470
380	0.1154	0.0324	28.0749	1144.67	771.41	67.3919
390	0.1086	0.0301	27.7668	600.13	704.27	117.3526
400	0.1050	0.0298	28.3633	651.00	447.77	68.7825
410	0.1011	0.0289	28.6072	687.40	619.22	90.0807
420	0.0969	0.0292	30.1761	547.87	470.40	85.8602
430	0.0936	0.0289	30.8870	935.67	752.52	80.4259
440	0.0880	0.0271	30.8456	734.93	436.00	59.3251
450	0.0836	0.0282	33.6901	1157.20	973.16	84.0964
460	0.0766	0.0250	32.5798	665.87	374.11	56.1834
470	0.0726	0.0248	34.2011	728.53	711.27	97.6307
480	0.0683	0.0237	34.7231	532.47	544.43	102.2471
490	0.0651	0.0237	36.3724	498.33	710.49	142.5734
500	0.0621	0.0225	36.1722	836.93	935.16	111.7360
510	0.0571	0.0205	36.0038	9497.20	3303.41	34.7830

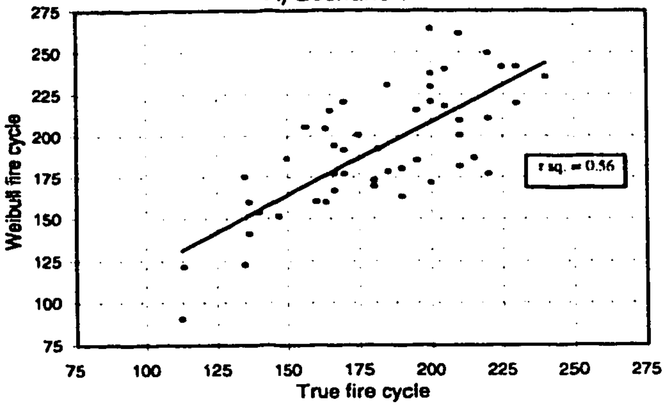
APPENDIX E

Figures showing the relationship and time difference between:
-the Weibull fire cycle and the average age of the forest
-the Weibull fire cycle and the true fire cycle

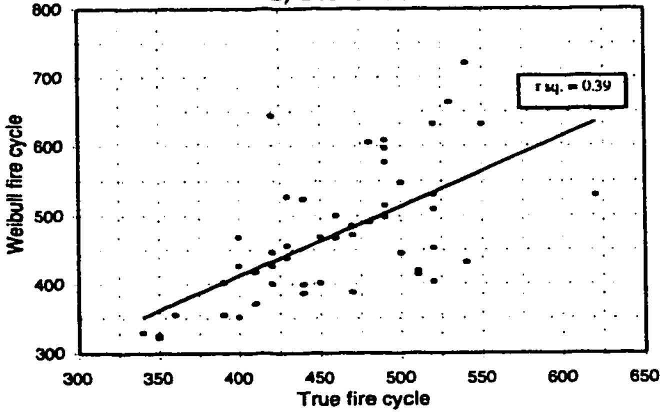


Strength of the relationship between the *Weibull fire cycle* and the *average age of the forest.*

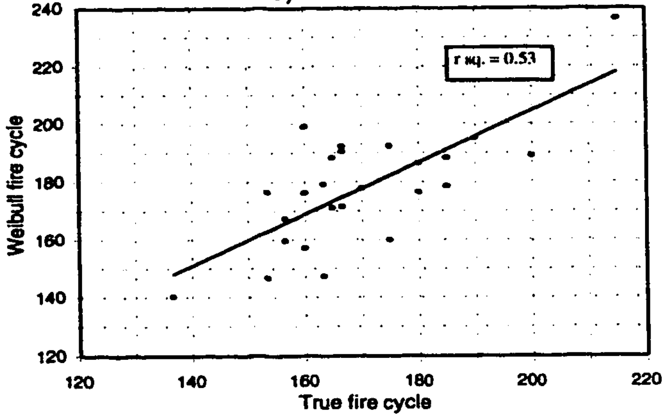
A) Scenario 1



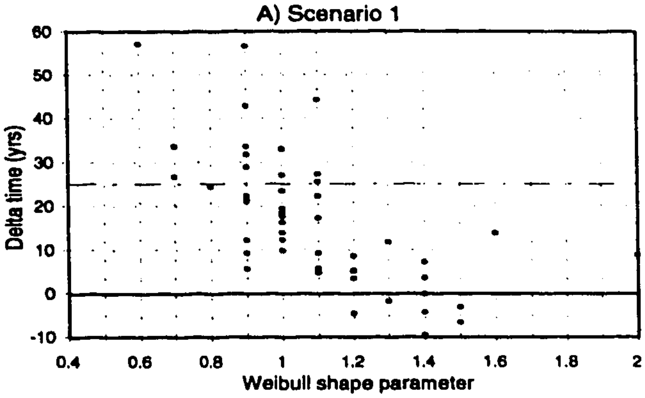
B) Scenario 2

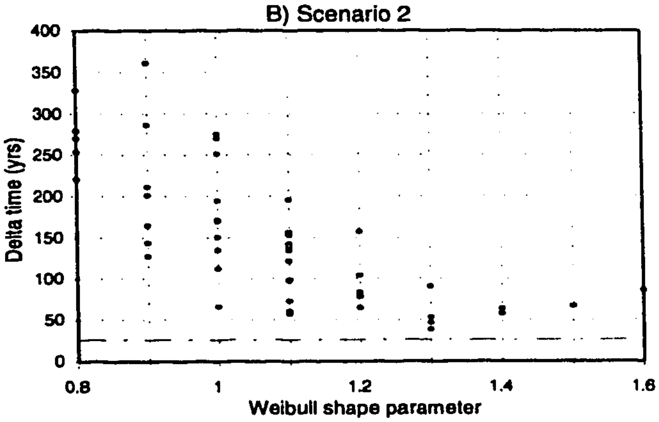


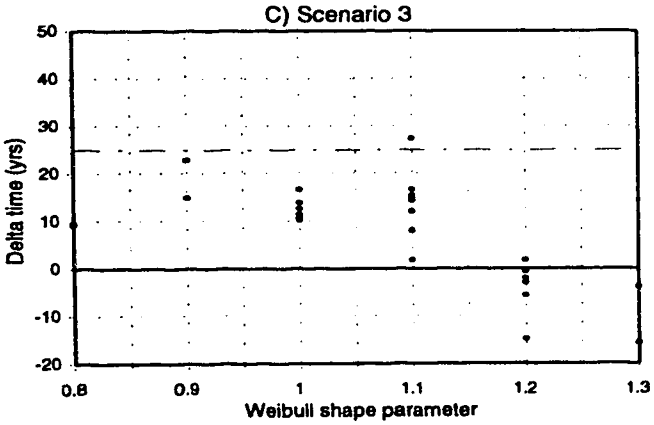
C) Scenario 3



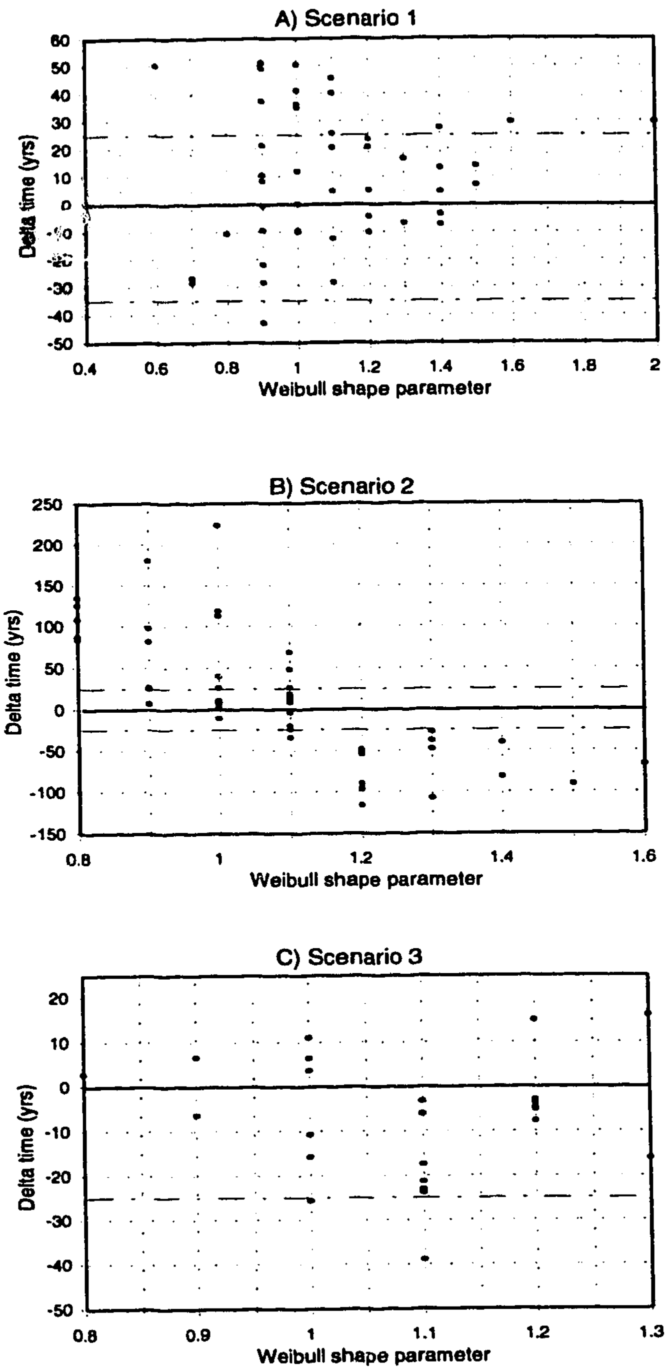
Strength of the relationship between the *Weibull fire cycle* and the *true fire cycle*.







Time difference between the *Weibull fire cycle* and the *average age of the forest.*



Time difference between the *Weibull fire cycle* and the *true fire cycle.*

APPENDIX F

Values of Weibull fire cycle, true fire cycle, and average age of the forest for simulated survivorship distributions

Scenario 1

Simulation	scale	shape	Weibull fire cycle	true fire cycle	average age of the forest
1	169.7	0.9	186.67	215.00	164.30
2	186.9	0.9	205.59	156.67	173.70
3	200.5	1	200.50	210.00	182.00
4	161	0.9	177.10	220.00	164.90
5	215.8	1.4	194.22	166.67	190.60
6	151.4	1.1	151.40	146.67	142.20
7	186.1	1	186.10	150.00	168.40
8	180.2	1	180.20	190.00	156.70
9	240.1	1	240.10	205.00	213.00
10	230.6	1.1	230.60	185.00	203.30
11	242.4	1.4	218.16	205.00	211.00
12	168.6	1.2	151.74	146.67	156.30
13	244.4	1.2	219.96	230.00	214.70
14	268.3	1.3	241.47	225.00	229.70
15	241.9	1	241.90	230.00	208.90
16	154	0.8	169.40	180.00	144.90
17	191.5	0.9	210.65	220.00	179.00
18	215.5	1.1	215.50	195.00	198.20
19	204.5	1	204.50	163.33	188.20
20	177.6	1.4	159.84	163.33	169.30
22	237.4	0.9	261.14	210.00	204.50
23	245.2	1.2	220.68	200.00	212.10
24	125.6	0.7	163.28	190.00	136.50
25	198.1	1.3	178.29	185.00	180.10
26	161	0.9	177.10	166.67	155.70
27	160.2	1	160.20	160.00	150.40
28	200.6	1.1	200.60	175.00	175.00
29	177.9	1.2	160.11	136.67	156.70
30	157	1.4	141.30	136.67	141.40
31	143.6	0.6	215.40	165.00	158.20
32	170.9	1.5	153.81	140.00	160.50
33	277.4	1.6	249.66	220.00	235.70
34	175.1	1.1	175.10	135.00	152.80
35	190.5	0.9	209.55	210.00	180.70
36	261.8	1.2	235.62	240.00	230.60
37	192	1.4	172.80	180.00	177.10
38	185	1	185.00	195.00	171.10
39	263.8	1.1	263.80	200.00	219.50
40	220.5	1	220.50	170.00	201.00
41	171.6	1.1	171.60	200.00	166.90
42	82.4	0.9	90.64	112.50	81.40
43	196.6	1.5	176.94	170.00	180.10
44	166.8	1	166.80	166.67	154.50
45	122.7	1.1	122.70	135.00	11.00
46	255.1	2	229.59	200.00	220.70
47	110.5	0.9	121.55	113.33	116.00
48	215.7	0.9	237.27	200.00	194.40
49	139.7	0.7	181.61	210.00	148.00
50	173.8	0.9	191.18	170.00	170.10
		Average:	192.23	181.55	173.51

Scenario 2

Simulation	shape	scale	Weibull fire cycle	true fire cycle	averageage of the forest
1	1.1	468.7	468.7	450	329.7
2	1.1	548.1	548.1	500	352.3
3	1.2	429.6	386.64	440	321.8
4	1.6	503.4	453.06	520	367.5
5	1.1	485.6	485.6	470	332.4
6	0.8	603.8	664.18	530	335.5
7	1	632.5	632.5	520	362.1
8	1	643.7	643.7	420	368.1
9	1.2	494.7	445.23	500	341.1
10	1.1	456.4	456.4	430	321.9
11	1.1	438.6	438.6	430	316.6
12	1.2	588.5	529.65	620	372
13	1.1	402.6	402.6	390	304
14	0.8	550.4	605.44	480	325.7
15	1.1	400.3	400.3	420	302.9
16	0.9	426.9	426.9	420	299.3
17	1	531	531	520	336.3
18	1	472.3	472.3	470	321.6
19	0.9	388.1	426.91	400	283.1
20	1	608.8	608.8	490	357
22	1.2	446.3	401.67	450	322.7
23	1	498.2	498.2	490	327.9
24	1	500	500	460	329.8
25	1.2	448.5	403.65	520	325.7
26	1.1	468.8	468.8	400	326.1
27	1	509.4	509.4	520	337.8
28	1.3	391	351.9	400	305.6
29	1	329.8	329.8	340	263.7
30	1.1	395	355.5	390	298.5
31	1.4	431.4	388.26	470	330.9
32	1	417.5	417.5	410	304.8
33	1.3	413.1	371.79	410	318.9
34	1	446.3	446.3	420	311.2
35	0.9	655.2	720.72	540	359.5
36	0.9	574.4	631.84	550	345.1
37	0.8	524.6	577.06	490	323
38	1.1	325.8	325.8	350	265.4
39	1.5	465.5	418.95	510	352.6
40	0.8	476.3	523.93	440	302.9
41	0.9	479.9	527.89	430	316.4
42	0.8	543.2	597.52	490	327
43	1.1	491.2	491.2	480	334.3
44	1.1	355.8	355.8	360	283
45	1.3	480.1	432.09	540	341.8
46	1.4	443.9	399.51	440	336.2
47	0.9	425.2	467.72	460	302.7
48	1.3	358.5	322.65	350	284.3
49	1.2	459.6	413.64	510	330.1
50	0.9	468.3	515.13	490	313.8
		Average:	473.28	459.8	323.93

Scenario 3

Simulation	scale	shape	Weibull fire cycle	true fire cycle	average age of the forest
1	188.37	1.1	188.37	165	173.01
2	236.3	1.1	236.30	215	208.98
3	169.4	0.9	186.34	180	163.59
4	190.5	1.1	190.50	167	175.58
5	190.5	1.2	171.45	167	174.43
6	133.4	0.9	146.74	153	131.88
7	216.9	1.2	195.21	190	193.38
8	195.8	1.3	176.22	160	191.91
9	177.4	1.2	159.66	157	174.53
10	199	1.1	199.00	160	197.2
11	156.02	1.2	140.42	137	141.13
12	142.9	0.8	157.19	160	147.89
13	177.89	1.2	160.10	175	165.75
14	188.94	1	188.94	200	175.12
15	163.7	1.3	147.33	163	151.23
16	179.1	1	179.10	163	168.95
17	188.37	1.1	188.37	185	174.09
18	176.42	1	176.42	180	165.01
19	167.42	1	167.42	157	156.75
20	171.12	1.1	171.12	165	163.13
21	197.55	1.2	177.80	170	179.89
22	178.55	1	178.55	185	165.95
23	192.5	1.1	192.50	175	175.92
24	192.28	1	192.28	167	175.71
25	176.41	1.1	176.41	153	164.41
		Average:	177.75	169.93	170.22