Restoration of the Clanwilliam cedar, *Widdringtonia cedarbergensis*: a study on the potential for fire as a management tool.

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***Widdringtonia cedarbergensis* in the Cedar Reserve.**

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Abstract

Flammability tests were undertaken on the foliage of W.cedarbergensis. Juvenile foliage was found to be more sensitive to heating than adult foliage on the same tree, while foliage collected from the top of the canopy was more tolerant to heating than foliage from the base of the canopy in the same tree. The sensitivity to heating did not differ between two geographically separate populations, one from a dry site and the other from a moist site. Foliage was more resistant to heating in winter than in summer. The sensitivity of foliage to heating did not correlate with the moisture content of that foliage. Factors influencing the survival of W.cedarbergensis in fire were explored at five sites by examining the characteristics of trees which survived and were killed by fires. Fire intensity had a major impact on survival at all five sites. At four of the sites the size of the trees, their crown base height, shape and degree of protection by rocks all influenced whether they survived or not. At the fifth site, none of the variables measured had a significant bearing on whether the trees survived or not. A sensitivity analysis to determine the relative importance of the various stages of the cedars life cycle in influencing population growth was calculated. The large seed producing trees were found to make the major contribution to population growth. A model using data on fire mortality collected in the field was developed to investigate the implications of various management options for the conservation of the cedar. This model predicted that an interval of fifteen years between typical intense summer wildfires will result in the rapid extinction of the species, while late summer/autumn prescribed burns require a minimum interval of 12 years between fires. The model predicted that conservation of the natural cedar forest at Die Bos will require complete protection from fire for at least 50 years. The model's simulations emphasised the importance of ensuring low mortalities in the largest size classes in prescribed burns as well as the value of the addition of nursery reared seedlings after fire. The model predicts that the present management strategy in the cedar reserve will be effective if mortality of existing trees in prescribed burns is minimized.

INTRODUCTION

W. cedarbergensis (Marsh) is a member of the family Cupressaceae, confined to the Cedarberg mountains of the south western Cape Province, South Africa. The species is currently classified as 'vulnerable', indicating its reduced status and that it could become endangered if the factors causing its decline continue to operate (Hall and Veldhuis 1985). This decline in status over historical time has been well documented (Hubbard 1937, Smith 1955, Luckoff 1972 Andrag 1977, Meadows and Sudgen 1991), while there has been a consistent concern expressed over its potential to survive in the future (Kruger and Haynes 1978, Manders 1986). As a result of its 'flagship' status and vulnerability to extinction, *W. cedarbergensis* has been the subject of scientific study for nearly 100 years and has been credited as the most researched indigenous plant species in the fynbos biome (Richardson 1993).

There has been much speculation as to why this species has undergone such a dramatic decline in status. According to Meadows and Sudgen (1991), the demise of the cedar must be viewed against a backdrop of late Quaternary environmental change which has led to alterations in the composition of the cedars co-occurring species and hence changes in fire regimes. Other authors have highlighted the over exploitation of the species as a timber source which resulted in a major decline in the healthy reproductively active trees (Smith 1955, Andrag 1977). However the most worrying aspect for managers of the Cedar is that despite prohibiting the felling of live cedars since 1876 (Andrag 1977), and engaging in a variety of proactive conservation and rehabilitation initiatives since the turn of the century, the status of the tree has continued to decline at an alarming rate.

The reason for this, and the problem central to the survival and hence management of the cedar, revolves around fire (Hubbard 1937, Luckhoff 1972, Andrag 1977, Kruger and Haynes 1978, Manders 1986, Manders etal. 1990). *W. cedarbergensis* grows in fire prone fynbos vegetation which naturally burns at an interval of approximately every sixteen years (Brown etal. 1991). The critical characteristic of *W. cedarbergensis* biology is its inability to resprout after fires. Thus individuals are killed by fire and rely entirely on successful regeneration from seed for recruitment. The enigma is that the cedar is a slow grower, which despite producing its first cones after about 12 years only reaches full reproductive maturity after 30 years (Andrag 1977); a period far longer than the average fire interval. A further dilemma facing management involves the season of burn. Tree survival varies with fire season and is generally best after winter or spring burns due to their lower intensity (van Wilgen 1980), however for recruitment cedars require high intensity fires such as occur in summer, and result in high adult mortality (Bond 1993).

Fire is the major manipulative tool available to managers for cedar conservation. Fire control was first initiated at the turn of the century when a complete ban on all fires in cedar areas was imposed (Bands 1981). However fire suppression proved impossible and the resultant wild fires were intense and burnt considerable areas of vegetation (Brown etal 1991). As a result, a policy of prescribed burning on a 12-year cycle was initiated in 1972 in an attempt to reduce the probability of large wild fires (Andrag 1977). Although this has been effective in reducing the number and frequency of wildfires, their average size has almost doubled (Brown etal 1991) and their impact on the status of *W. cedarbergensis* has in no way diminished. As a result many populations have been totally eradicated while the majority of those that remain are so reduced in numbers that natural regeneration can no longer occur (Manders and Botha 1987, Mustart 1993).

It is thus evident that past attempts at fire management in the Cedarberg have been largely ineffective as a means of cedar conservation. This has led to the initiation of a 'Cedar Reserve', an area set aside for pro-active re-establishment and conservation of W. cedarbergensis. The reserve is about 5 252 ha in extent and encompasses approximately 21% of the current cedar distribution (van der Merwe 1986). Its management strategy is separate to that of the remaining wilderness area where the objective is the maintenance of overall biodiversity (van der Merwe 1986). The management guidelines for the reserve require the application of short frequency, low intensity winter burns in order to reduce the loss of adult trees in wild fires (van Der Merwe and Wessels 1993). The problem of low germination after these cool burns is resolved by boosting seedling numbers through large-scale plantings of nursery-grown seedlings in the newly burnt areas (Van der Merwe and Wessels 1993).

Although, at first glance, this strategy for cedar reserve management seems well defined and straight forward, the problems which have thwarted cedar fire management in the past remain major stumbling blocks to the implementation of this scheme (Wessels pers. comm.). The manager has important decisions to make as to where and when to burn in the reserve each year. When selecting a potential site for patch burning, or burning for planting, it is important to be able to predict what impact a controlled fire is likely to have on existing cedar stands. For this it is necessary to understand which factors enable certain trees to survive fires while others are killed and also whether the trees themselves change in their resistance to fire between seasons. This prediction for adult survival needs to be related to an acceptable level of adult mortality and in turn considerations of how many seedlings will need to be planted in order to ensure adequate artificial post-fire recruitment. A further important consideration relates to the interval required before a planted area is re-burnt so as to ensure adequate survival of the artificial regenerates.

This project aims to answer some of these questions relating to fire management of the cedar in general, and in particular within the cedar reserve. It is divided for convenience into three separate, but interrelated, components. Part A explores the significance of seasonal changes in the tolerance of foliage to fire and the potential of using this to determine the best time to burn. Part B examines the various factors which influence the level of mortality in fire, with the aim of predicting approximate mortality of a population in prescribed burns. Finally part C uses real data on mortality collected in the field and matrix modelling to examine a variety of management options relating to the manipulation of frequency and intensity of fire.

PART A Flammability tests.

Introduction

Fire mortality of *W.cedarbergensis* varies considerably, with figures as low as 6.5% during prescribed winter burns (van Wilgen 1979) and as high as 91% in summer wildfires (van der Merwe 1988) being recorded. These differences in mortality have in the past been ascribed exclusively to differences in fire intensity. However it has recently been suggested that mortality in cedars may depend more on the condition of the plant than on fire intensity (Bond 1993). Cedar foliage is particularly sensitive to scorching and the majority of trees appear to be killed by crown scorch rather than cambium damage. Evidence for death by scorching can be seen after fires where numerous canopies are destroyed without actually igniting (pers. obs.). In some instances trees outside the path of the fire appear to have been killed by heat alone (pers. obs.).

It is therefore the sensitivity of the foliage to heat, rather than to the flames themselves, which will determine whether the plant will survive fire or not. Heated twigs of *W. cedarbergensis* "blush" from green to brown at their lethal temperature threshold (Bond 1993) (plate 1). This blushing can be used as an indicator to determine the sensitivity of cedar foliage to heat. Relative differences in resistance to the heat treatment are thus likely to be biologically valid simulations of the relative tolerances of individuals to fire.

The primary objective of the following experiments is to investigate whether the sensitivity of the species changes with season and if so whether this can be related to the moisture content of the foliage. A similar relationship has been documented by Xanthopoulos and Wakimoto (1992) for three western United States conifers, and could prove useful in providing a rapid test for managers to ascertain sensitivity levels of populations to fire. Secondary investigations will explore whether differences exist in the sensitivity to heat exposure between different size classes, between adult and juvenile growth forms, between upper and lower branches and between geographically separated populations.

Plate 1. Heat damaged foliage of *W.cedarbergensis* 24 hours after exposure to heat treatment in the oven. A - green foliage unaffected by heat, B - damaged foliage that has turned brown and will be unable to recover.

Sample sites

Three sampling sites were used for these experiments at De Rif (site 1), Sederkop (site 2) and Welbedacht (site 3), and are demarcated in fig.1. The De Rif samples were collected from within the plantation at the old farmstead of the same name. This site is shaded and occurs on damp soils. Sederkop is the name I gave to the conspicuous cedar population which is situated west of De Rif, above the footpath leading from Driehoek farm to De Rif. This cedar clad ridge was previously delimited as part of a phytosociological study of Cedarberg plant communities (Taylor <u>in prep</u>). Taylor's plot number for this site is HCT 860016. The sampling at Welbedacht was carried out on three trees growing in close proximity to each other, approximately 1 kilometre south east of the nursery.

Methods

Circa 30 cm long branch tips of *W.cedarbergensis* were collected during three field trips in March, May and July 1994. The March field trip was used to collect the following samples for a pilot study;

* Branches from class eleven trees at two separate sites, in order to test whether differences exist between trees at a wet (De Rif) and a drier (Sederkop) site.
* Differences in flammability between class 2 seedlings (only juvenile foliage) and the largest size (class 11) trees (only adult foliage) was also examined.
* Branches from class three trees with both juvenile and adult foliage on the same branch. These were used to examine whether differences exist between the flammability of adult and juvenile foliage growing on the same tree.
* Branches from the top and bottom of the crown to test for differences within a single tree.

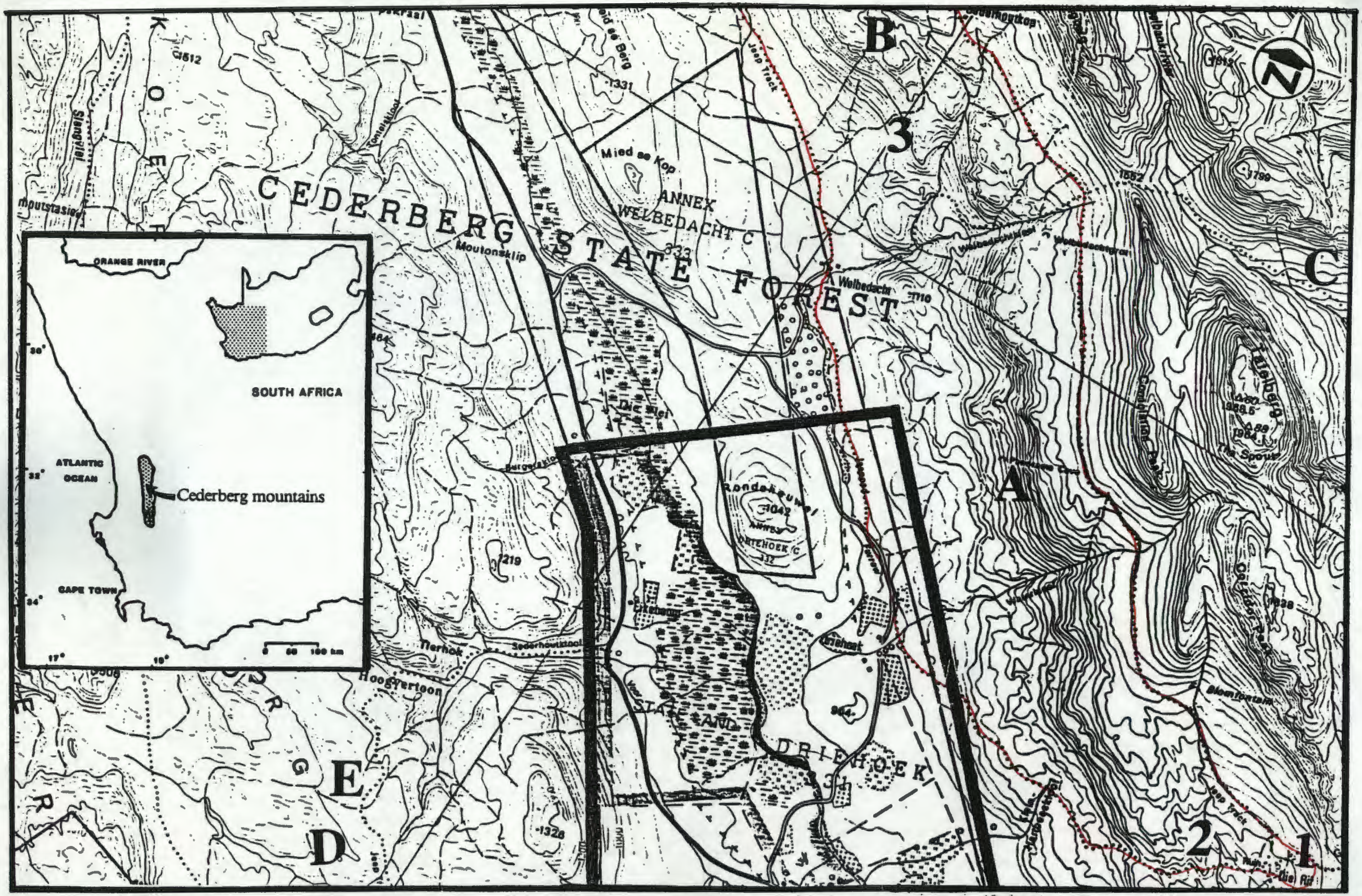

Fig.1 Locality of study sites. 1. Die Rif, 2. Sederkop, 3. Welbedacht - relate to part A. A. Panwin, B. Donkwin, C. Forestsum, D. Sneeusum and E. Hoogsum - relates to parts B and C of text. Map insert is locality of Cedarberg. Red line demarcates boundaries of the Cedar Reserve.

In all cases five replicates from each of five trees was collected. The May and July field trips were then used to determine whether the flammability of *W. cedarbergensis* changes with season. Three class eleven trees were selected at Welbedacht and five branches were removed from each tree in May and again in July. In all cases the branches were sealed in plastic bags immediately after cutting, whereafter they were transferred to a 0°C room within 24 hours and stored until required.

The methodology for testing flammability was developed during similar tests which examined the relationship between xylem potential and damage to foliage at various temperatures and time intervals (Honig and Bond unpublished data). The results of this study indicated that the complete range of damage to cedar foliage could be achieved by placing branches in an oven at 80°C for various time intervals up to two minutes.

Small branchlets (8-10 cm long) were thus cut from each branch and subjected to a temperature of 80°C in an oven for one of 11 different durations between 5 seconds and 2 minutes. After 24 hours the degree of damage was scored according to the following five categories:

0 = no change
1 = branch tips turned brown
2 = < 1/2 the branch turned brown
3 = > 1/2 the branch turned brown
4 = entire branch turned brown

Variation in moisture content was obtained through placing a sample of green leaf material in a petri dish of known weight, weighing on a balance to a precision of 0.0001 g, placing in a drying oven at 100°C for 48 h, and reweighing. Care was taken to ensure that only fresh green foliage was sampled for moisture content.

Statistical analyses

The mean damage of the five replicates at each time interval was calculated. This resulted in a set of matched pairs of damage for each time interval in the oven for each test. Owing to the non-normality of this data it was necessary to make use of the non-parametric Wilcoxon paired-sample test which is analogous to the paired sample t test for normal data (Zar 1984). It thus tests the null hypothesis that the two samples are from the same population.

A regression equation was calculated to determine the relationship between plant moisture content and the degree of damage for experiments involving trees with adult foliage. Juvenile foliage was excluded owing to its much higher moisture content. For each experiment (eg. lower branches) the mean of the damage for all exposure times was calculated, as was the mean moisture content. These values were then regressed against each other with moisture content as the independent variable. All statistics were calculated using the statistical software package Statgraphics.

Results

Spatially separated populations.

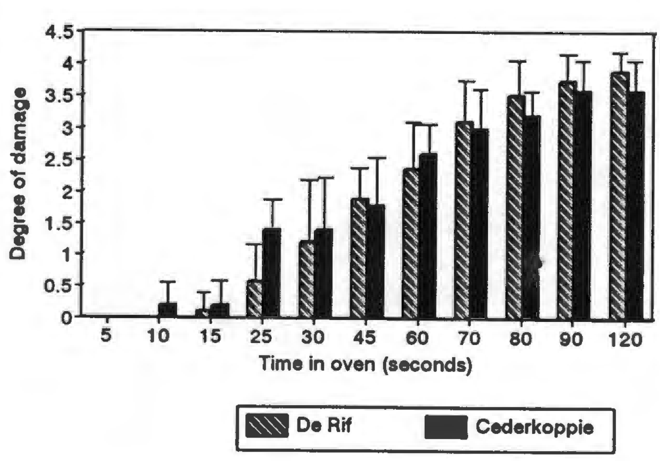

Fig. 2. Flammability of class 11 trees from geographically separated populations. Values are means of five branchlets.
(Wilcoxons two-tailed probability = 0.333, accept H_0)

There was no significant difference in the flammability of the class 11 trees from De Rif and Sederkop. The mean moisture content of the foliage sampled at De Rif was 50.475 % (sd.2.15%) as against the 48.75 % (sd.0.94%) of the trees growing at the drier Sederkop site.

Different size classes.

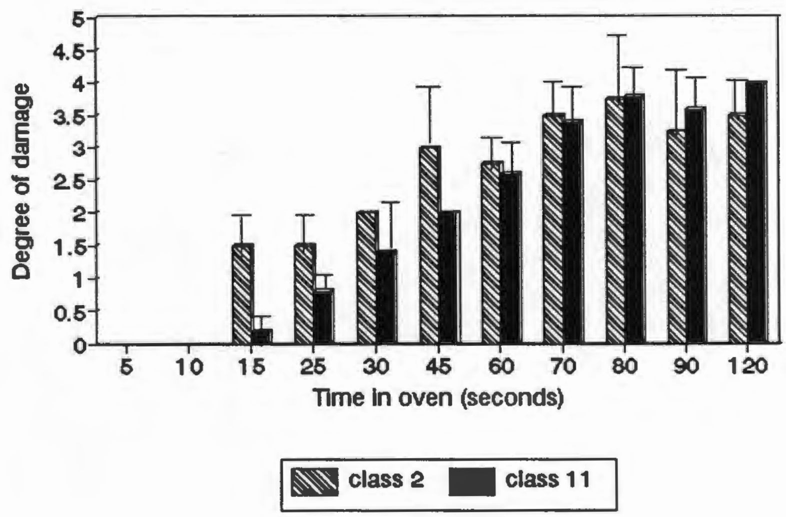

Fig. 3. Flammability of foliage from the two extreme size classes. (Wilcoxons two-tailed probability = 0.124, accept H_0)

The juvenile foliage of the class two trees is more sensitive to heat over the shorter exposure times (15 - 45 s). Over the longer intervals the adult foliage is slightly more sensitive. Overall the juvenile vegetation was more sensitive to heat, however the two size classes do not demonstrate a significant difference in their response to heat treatment. The mean moisture content of the class two samples was 60.75 % (sd.4.1%) whereas that of the class 11 trees was 49.53 % (sd.0.82%).

Adult and juvenile foliage

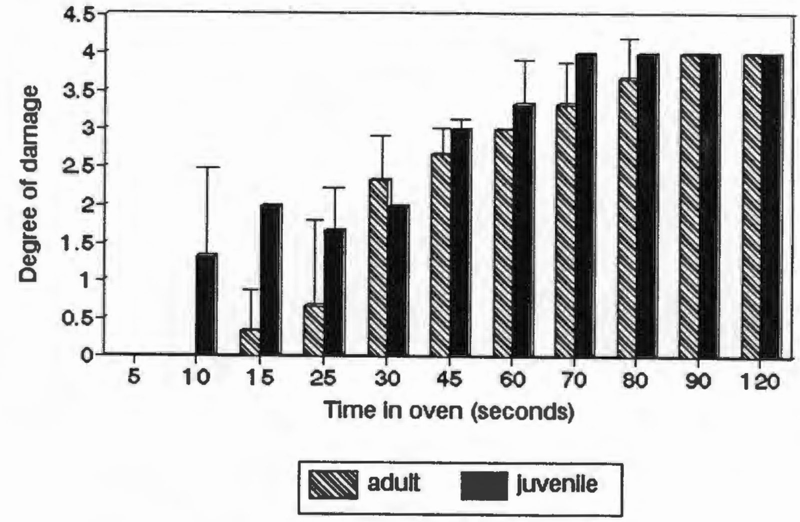

Fig. 4. Flammability of adult and juvenile foliage growing on the same trees. (Wilcoxons two-tailed probability = 0.0254, reject H_0)

The juvenile foliage is more vulnerable to heat treatment, especially at the low exposure times (10 to 25 s), than the adult foliage. The mean moisture content of the adult foliage was 57.71 % (sd.1.76%) and the juvenile foliage was 56.32 % (sd.1.61%)

Upper and lower branches.

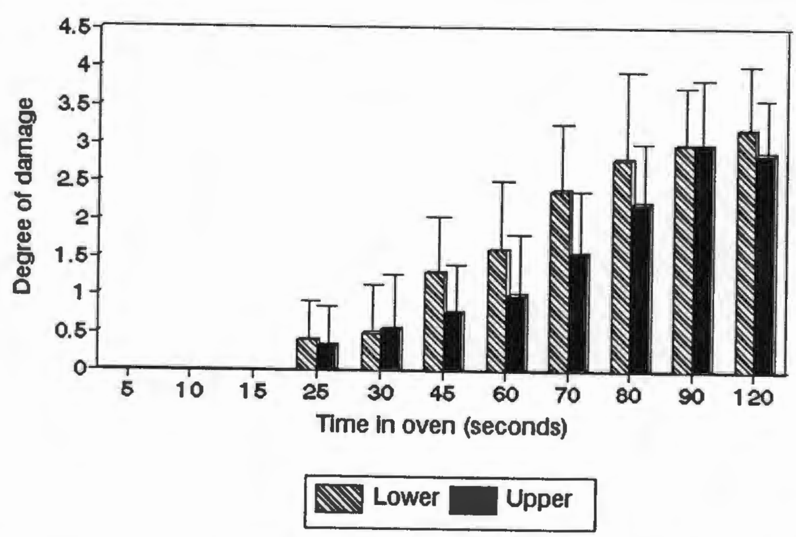

Fig. 5. Flammability of the lower and upper branches of class 11 trees growing at Welbedacht. (Wilcoxons two-tailed probability = 0.0225, reject H_0)

There was a significant difference in the response of upper and lower branches to the heating treatment. The sixty to eighty second exposure times resulted in differences of greater than 0.5 in the degree of damage between upper and lower branches. The mean moisture content of the lower branches was 47.97 % (sd.2.45%) as against the 52.98 % (sd.1.7%) of the upper branches sampled.

Temporal separation.

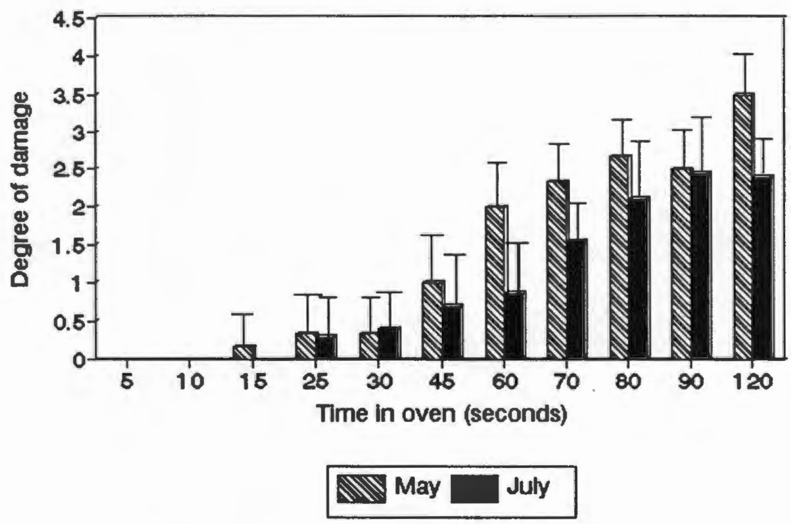

Fig. 6. Flammability of foliage sampled from class 11 trees in autumn and winter. **(Wilcoxons two-tailed probability = 0.0178, reject H_0)**

The flammability of the foliage decreased in winter for all the exposure times. Consequently the temporal differences in sensitivity proved highly significant. The mean water content of the foliage sampled in May was 48.55 % and increased to 50.05 % in July.

Relationship between moisture content and heat exposure damage.

The R squared value of 0.265 (n = 11, DF = 9, p=0.1) indicates that the degree of damage is not closely related to the moisture content of the tree.

Discussion

Although there was no significant difference in the sensitivity of the extreme size classes to heat exposure, it would appear that juvenile foliage is more vulnerable to fire than adult foliage, despite its much higher moisture content. Plants bearing juvenile foliage rely on their atypical ability of undergoing epicormic resprouting in order to survive fires. However this adaptation to fire would only appear to be successful after very favourable cool fires (pers. observation) (plate 2). The very high mortality of juvenile individuals in all fires (see figure 7) is probably much more a function of their size than their greater sensitivity to the flames. Nevertheless this finding further highlights the extreme sensitivity of juveniles to fire.

The sensitivity to heat exposure of foliage collected from the lower branches of trees was significantly higher than that from the uppermost branches. Although this pattern is unexpected and may be a product of the small sample size, if valid it could be a weak form of adaptation to fire. Many trees are left with only the uppermost portion of the canopy after fire (plate 3) (pers. observation). Although it is to be expected that the highest mortality should occur near the ground where intensity is greatest, a slightly higher resistance to heat by the upper foliage may be a trait which augments their survival. A further advantage of preserving the upper foliage is that it bears the majority of the reproductive structures. The mechanism behind this attribute could relate to the measured increase of 5 % in moisture content of the upper foliage when compared with the lower foliage. This in turn could be a result of the greater demand for water in the younger actively growing upper foliage.

There was no evidence for differences between populations in the sensitivity of class 11 trees to heat exposure. Despite the sample sites having been especially chosen for their differences in microclimate, the moisture content of the trees growing adjacent to a spring at De Rif was only 1.75 % higher than those

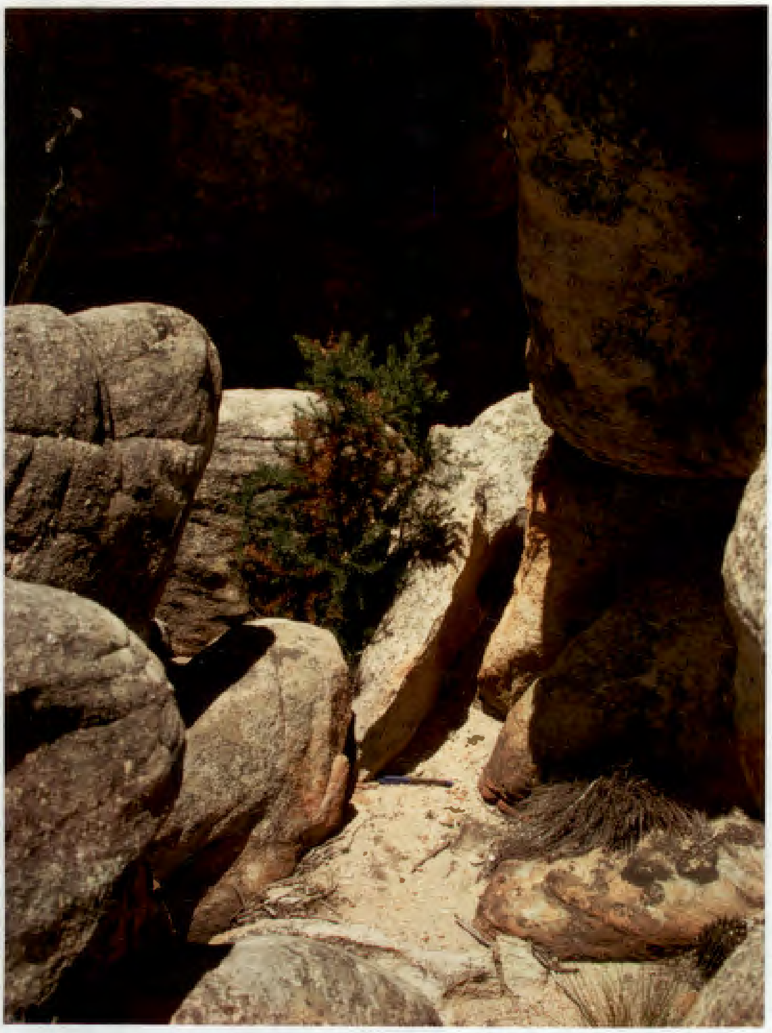

Plate 2. A young cedar scorched by a prescribed burn in the cedar reserve. Fresh foliage which sprouted since the fire is clearly evident.

Plate 3. An adult cedar with much of its trunk and lower branches killed by fire but upper canopy undamaged and carrying cones.

sampled from the dry Sederkop site which had received virtually no moisture for eight months. However recent findings by Cohen etal. (1989 - cited in Rothermel 1991) have shown that tree branchlets are able to release large amounts of moisture to the air when heated. Furthermore this effect was shown to be possible only when adequate soil moisture is available. As an example, *Pinus contorta* needles which released moisture were found to require 49% more energy to reach ignition than specimens without this capability (Rothermel 1991). It is thus likely that although laboratory investigations found minimal differences in flammability between the two sites, the greater potential for the De Rif population to rapidly draw on soil water resources when heated would increase their resistance to a fire relative to the drier Sederkop population.

As a result of methodological error in the March sampling, only two temporally separated experiments were undertaken. Fortunately virtually no rain had fallen in the eight months prior to the May sampling trip, whereas 376.2 mm fell between the May and July trips (Algeria weather station). During this time the sensitivity of the foliage from each of the three trees sampled decreased significantly. This suggests that physiological changes within a single tree over time can reduce its vulnerability to fire. Given the findings of Rothermel (1991), it is also possible that the trees insitu resistance to fire would be further increased after rains by the greater soil moisture availability. It is however uncertain whether the changes measured in the laboratory experiments would result in a significant increase in the survival of the tree in a fire. This uncertainty exists because we still do not know the relative importance of fire intensity versus tree state in influencing fire survival. The above investigations have demonstrated that the physiological status of the tree can influence foliage flammability. However further research is needed to investigate how differing fire intensities influence the mortality of trees with the same sensitivity to fire.

It was hoped that the sensitivity status of a population could be determined and combined with fire intensity projections to improve the predictions for suitable burning times. Unfortunately the moisture content, which it was thought might be useful as an indicator of sensitivity, does not correlate with the level of damage experienced by a tree. This is despite increases in moisture content relating to increases in tolerance in all the significant experimental results discussed above. Sensitivity of foliage to fire is not driven by a simple moisture content relationship and it is therefore not possible to use this measure to make predictions with regards a populations sensitivity to fire. Future research should be aimed towards increasing knowledge on changes in tolerance throughout the year and finding correlations between these changes and some easily measurable parameter such as plant water potential or soil water content. From this limited study it would however appear that seasons of lowest fire intensity do correspond with the trees period of greatest physiological resistance to fire.

PART B Factors influencing survival of *W. cedarbergensis* in fire.

Introduction

Prescribed burning is the only viable management option for reducing fuel loads and thereby diminishing the probability of intense wildfires destroying cedar populations. It is however essential that cedar mortality be kept to a minimum in these burns. At first appraisal W.cedarbergensis, unlike most other fynbos species, appears to have no effective traits for fire survival. However, Kruger and Haynes (1978) found a high proportion of living trees bearing fire scars, thus indicating that some cedars are able to survive fires. When selecting sites for prescribed burning it is important to be able to predict the expected mortality of trees in a given population, in a given fire. As discussed in part A, fire intensity as well as the physiological status of the tree will influence cedar mortality in fire. Both these variables can, to a degree, be controlled by management. This section examines other characteristics of a population which might influence its survival in fire. Similar studies using multivariate techniques have been undertaken in Californian redwood forests to distinguish between trees destined to die and those that will survive prescribed burning (Finney and Martin 1992). In these studies the height of trees and foliage height above ground (crown base height) have proven significant predictors of tree mortality in fire (Finney and Martin 1992).

Manders (1986) suggested that factors affecting survival of *W.cedarbergensis* in fire include fuel load and weather conditions (both relating to intensity) as well as the size of the tree and rockiness, while I have added to these the trees shape and crown base height. An understanding of which of these factors, if any, promote cedar survival in fire has important implications for the choice of sites to burn, as well as in planting programs.

Methods

Study sites.

Five study sites were selected to cover the requirements of both parts B and part C of this study. These sites were all burnt within the last decade, showed differing degrees of cedar survival, and had experienced fires of differing intensities. Their locality is given in Fig 1. Sites A and B are situated within the cedar reserve and were burnt in a controlled early winter burn in 1989 (Hendricks pers.comm.). The cedar populations at both these sites had previously been enumerated for a demographic study (Marais unpublished data). At the time of the fires the vegetation at both sites A and B was well in excess of 40 years old (Table 1). Site C is situated at De Bos, within the last remaining natural cedar forest. This closed canopy forest was burnt out by a wild fire during an extremely dry spell in November 1984 (van der Merwe 1988). The age of two felled trees at this site was found to be in excess of 200 years. The absence of fire scars on any of the growth rings analyzed suggests that the area had not experienced fire for at least this time span. Site D and E are situated at the Hoogvertoorn and Sneeuberg sites used by Manders in developing his transition model. These two sites were burnt in the same summer wild fire in December 1988. The vegetation was thirteen years old at the time of the fire.

Table 1. Details of plots used in parts B and C.

Plot	Name	Date and nature of burn		Approx. Veg.Age at burn (yrs)
A	Panwin	May 1988	(prescribed burn)	>40
B	Donkwin	May 1988	(prescribed burn)	>40
C	Forestsum	November 1984	(wildfire)	>200
D	Sneeusum	January 1989	(wildfire)	13
E	Hoogsum	January 1989	(wildfire)	13

(Pan from Panorama which is locality name and win from fire season, winter)

Data collected

At each of the five sites a random sample of approximately two hundred trees was examined to determine the survival of all size classes following the differing intensity fires. At Panwin and Donkwin the trees which had been randomly selected and tagged with metal stakes for an earlier study were sampled. At the other three sites the trees were randomly chosen by sampling the first 200 individuals encountered along a line transect. Using Manders (1987) size class categories, trees less than 150 cm were allocated to classes 2 to 6 on the basis of height, whereas trees taller than 150 cm were allocated to classes 7 to 11 on the basis of DBH (appendix 1). The trees were classified as either having survived (s), been killed (k) or having not been reached (e) by the fire (table 2).

A separate survey was employed to collect data on equal numbers of living and dead trees in an attempt to determine which variables best predict a trees survival or death in fire. At each of the sites approximately 100 trees were selected and their status (alive or dead) recorded. Where possible trees were chosen so as to be representative of all size classes. Owing to a shortage of living trees at some sites, more dead than living trees were surveyed and it was not always possible to include equal numbers of the various size classes.

For each of the trees selected the following characteristics were noted:

i. **Tree height.** Height in meters was measured, with the aid of a clinometer for the taller trees

ii. **Stem diameter.** Diameter of the stem 1 metre above the ground was measured for all trees > 1.5 m tall.

iii. **Crown base height**. The height of the lowest living foliage above the ground at the time of the last fire was measured and categorized according to the following index:

1. < 1.0 m
2. 1.0 - 2.5 m
3. 2.5 - 5.0 m
4. > 5.0 m

iv. **Rock protection.** An index was formulated to classify the degree of protection offered by surrounding rocks. This is analogous with an index of decreasing fuel load.

1 - Entirely surrounded by undergrowth.
2 - < 50 % Protection by rocks.
3 - > 50 % Protection by rocks, but with some undergrowth accessible to fire.
4 - Entirely surrounded by rocks.

v. **Tree Shape.** The shape of the tree was classified according to one of the following categories:

1 - Conical shaped with single main stem (including juveniles with no main branching).
2 - Main stem branched (branching < 3m above ground).
3 - Single straight stem, only branching > 3m above ground.
4 - No main stem (branching outwards from ground level).

The trees were allocated to the 11 size classes of Manders (1987) according to their height (if < 150 cm) or otherwise their diameter at breast height (appendix 1). The surveyed trees provided an uneven spread between these classes, with some classes having very few individuals and others many. The classes were therefore grouped as follows:

Manders (1987) classes	New classes
2 to 6	class 1
	(plants < 150 cm)
7 to 9	class 2
	(trees >150cm and diameter <20cm)
10 and 11	class 3
	(trees diameter >20 cm)

Combining winter and summer mortality data.

Although this data was collected at five geographically isolated sites, similarities existed between the fire intensities and therefore mortalities experienced by some of the sites. Panwin and Donkwin which had equal aged vegetation were burnt separately, but at the same time of the year, while Sneeusum and Hoogsum were burnt in the same fire. The data collected on the levels of mortality of 200 randomly selected trees at each site was used to ascertain whether mortality of each size class was comparable between any of the sites using chi-squared goodness-of-fit analysis on Statgraphics. The assumption being that sites with similar proportions of mortality in all size classes experienced equal intensity burns and can thus be combined to increase sample size.

Statistical analyses

The computer software package GLIM (Generalised Linear Interactive Modelling) was used to assess the affects of the four variables; tree class, rock protection, shape and crown base height on the probability of survival of a tree during fire. This package makes use of generalised linear modelling (McCullagh and Nelder 1983) to define a logistic regression for the relationship between these variables and the status (dead or alive, ie a binomial function) of the tree. Each of the four variables were individually entered into the model as the only explanatory variable for the probability of survival (the marginal effect). They were also entered in conjunction with the other explanatory variables to examine their partial effect on survival. A variable that is significant with regards both its marginal and partial effects should be retained as an explanatory variable (Mustart etal. in press). The raw data which was used in the GLIM analysis, together with the GLIM printouts showing the outputs of the statistical operations are presented in appendix 2.

Results

Table 2. Percentages of the total trees enumerated at each site which were killed, not reached by, or survived the fire.

Site	n	% killed	% survived	% not reached	% alive after fire
Panwin	110	67.3	8.2	24.5	32.7
Donkwin	105	53	27	20	48.6
Forsum	227	56	13.7	30.3	44.1
Sneeusu	190	86.8	7.4	5.8	13.2
Hoogsum	208	76	13.5	10.5	24

Mortality in fire was over 50 % at all the sites examined. The lowest mortality in fire was recorded at Donkwin. The higher survival at Panwin, Donkwin and Forestsum was largely a result of the large number of trees which were not reached by the fires.

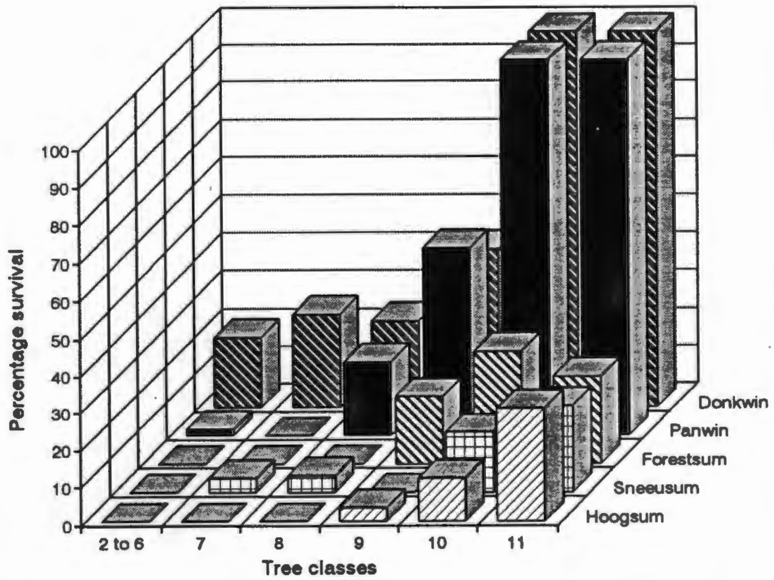

Fig 7. Survival of trees in the various size classes that were reached by the fire at each of the five sites.

All the size classes suffered higher mortalities in the wildfires (C, D and E) when compared with the controlled burns (A and B). Survival was low in the smaller size classes in all fires, whereas in the larger size classes survival was much higher in the prescribed burns than in the wildfires. It is important to note that the majority of trees at Panwin and Donkwin were in the smaller size classes, whereas at Forestsum, Sneeusum and Hoogsum most trees were in the larger classes (9 - 11).

Table 3. Chi squared goodness-of-fit tests to determine whether fire mortality at sites are similar enough to group them. (figures in table are p values)

	A	B	C	D	E
A		0.1295	0.000 **	0.000 **	0.00978 *
B			0.00 **	0.000 **	0.0978 *
C				0.9078	0.4546
D					0.9858

* p < 0.5 ** p < 0.05

The chi-squared analysis on the class survival proportions at the various sites indicated that there were no significant differences between mortality in the two controlled winter burns (sites A and B), or between the two summer wildfires (sites C and D). There was however a significant difference between the mortalities of the summer and winter burns. It was thus possible to group the data from Panwin with Donkwin and from Sneeusum with Hoogsum. Forestsum, despite its similarity with Sneeusum and Hoogsum, was analyzed separately owing to the unique characteristics of the population at this site (see discussion).

Table 4. The percentage of the total trees enumerated within each category of the four variables which survived fire. This data only includes trees which were reached by the fire.

		Class			Shape				Foliage height				Rock protection			
		1	2	3	1	2	3	4	1	2	3	4	1	2	3	4
LOW INTENSITY SITES A & B	Total number of trees observed	85	55	17	137	16	0	4	139	11	5	2	95	34	24	4
	% survival	7.1	22	100	15	69	/	100	14	90	80	100	1.6	22	67	100
HIGH INTENSIT SITES D & E	Total number of trees observed	29	66	77	61	86	7	18	67	68	23	14	54	34	56	28
	% survival	6.9	24	66	8.2	58	86	64	11	49	70	61	13	41	59	67
FORESTSUM Site C	Total number of trees observed	1	28	50	18	36	24	1	59	12	5	3	60	8	11	0
	% survival	0	36	54	33	39	67	100	56	50	40	33	50	25	45	0

At all sites the percentage of trees surviving the fire increased with the size of the tree. However at forestum only one tree in the smallest size classes was found making the relationshp at that site unclear. Relative to the other categories, survival was very low for the unbranched conically shaped trees (shape class 1) at the low and high intensity sites. With the exception of Forestsum survival generally increased with increases in rock protection as well as crown base height.

Glim analysis

Table 5. Analysis of deviance of the four variables in the low intensity fires (sites A and B)

	Effect			
Variable	df	Marginal	df	Partial
Class	2	69.55 **	11	98.42 **
Shape	2	44.5 **	11	109.52 **
Foliage Ht.	3	53.39 **	10	107.83 **
Rocks	3	53.54 **	10	102.21 **

** p, 0.01 * p < 0.05

Table 6. Analysis of deviance of the four variables in the high intensity fires (sites D and E).

	Effect			
Variable	df	Marginal	df	Partial
Class	2	45.53 **	9	82.41 **
Shape	3	45.93 **	8	79.97 **
Foliage Ht.	3	48.71 **	8	71.57 **
Rocks	3	51.43 **	8	70.31 **

** p, 0.01 * p < 0.05

Table 7. Analysis of deviance of the four variables. Data collected from Forestsum (site C)

	Effect			
Variable	df	Marginal	df	Partial
Class	2	3.7068 NS	8	9.995 NS
Shape	3	7.916 *	7	6.071 NS
Foliage Ht.	3	0.829 NS	7	12.579 NS
Rocks	2	1.867 NS	8	12.181 NS

** p, 0.01 * p < 0.05

The importance of the measured variables in influencing fire survival varies between sites. All four variables showed significant marginal and partial effects on the probability of *W. cedarbergensis* surviving fire in the intense fire (sites D & E) as well as the cooler fires (sites A & B). However only shape, which showed significant marginal affects, was found to influence survival at Forestsum.

Discussion

The high mortality at Sneeusum and Hoogsum of 81% corresponds well with other mortality figures for wildfires quoted in the literature, such as the 81.2 - 97% cited by Forsyth (1979) and the 91% of van der Merwe (1988). The cedar populations at Panwin and Donkwin also suffered surprisingly high mortalities during the controlled winter burns of 1988 (59.5 % of the trees sampled were killed by these fires). Previous reported surveys on mortality in prescribed burns have revealed much lower values such as the 6.4% of van Wilgen (1980), and the 6 - 18% of Forsyth (1979). However the high mortality in this study is probably explained by the large proportion of juvenile cedars together with the occurrence of forty year old vegetation at the two sites. The survival in the individual age classes was nevertheless much higher than that for the wildfires. This was partly because of the considerably better survival of the larger size classes, but also because of the increased proportion of the total trees which were not burnt at all in the patchy, low intensity fires. It would thus appear that the major differences between high and low intensity fires, with regards their impact on cedar mortality, is increased survival of the larger size classes and increased patchiness with reduction in intensity. The factors which influence the movements, and thus patchiness, of a fire are poorly understood. Both the rockiness of the terrain as well as fire intensity must be important in this regard. However an inability to quantitatively predict the movements of a flame front remain a major stumbling block to estimating the proportion of trees which will escape fire by not being burnt.

With the exception of the population at Forestsum, certain characteristics of the individual trees and their direct environment were found to influence the probability of their survival in fire. It is important to note that while GLIM calculates whether trees that survived fires have different characteristics to those that were killed, it takes no cognisance of the overall mortalities recorded in the different fire intensities discussed above. What is apparent from table 4, as well as observations in the field, is that as the intensity of the fire increases, so the influence of these characteristics diminishes.

The findings of this study indicate that with increasing size the probability improved of individuals surviving the fires at all sites except Forestsum. A number of authors have noted that bigger cedars have better survival rates in fire (Andrag 1977, Forsyth 1979, Manders 1986). While size in itself is important in promoting fire survival, other attributes related to a trees physiognomy also influence fire survival. In this regard the crown base height, although partly related to tree size, would appear to be an important autonomous characteristic influencing survival (see plate 3). Thus some very large trees having foliage in the undergrowth are likely to be more vulnerable to canopy damage than a smaller tree with branches a few metres above the ground. The results of the survey indicate that there is a general increase in survival with increasing crown base height. Tree shape was also found to be significantly related to fire survival. However this relationship is probably a corollary of the relationship between the four shape categories and their different sizes and foliage heights. Thus the low survival in shape category one at Sneeusum and Hoogsum is more likely a result of the trees belonging to the smaller size classes than the shape of the tree itself.

The protection afforded by rocks also plays a crucial role in promoting survival of cedars in fire. As the degree of rock cover around an individual increases so the level of combustible undergrowth decreases. Thus rocks act directly to reduce the intensity of fire. Rocks also act to isolate islands of vegetation from the fire, thereby preventing some cedars from being burnt at all (pers. obs.). Andrag (1977) noted that the majority of established trees which have previously survived fires grow in well protected rocky environments. Scattered individual trees with their foliage confined above large boulders are often the only surviving remnants of cedar populations in some areas (plates 4 and 5). Thus the degree of rockiness can be utilised by managers to assess the potential fatalities of cedars

Plate 4. The large rock in the foreground has provided these two cedars with essential protection from fires which generally move upslope (right to left). The unprotected side of the tree has experienced extensive foliage and cambium damage.

Plate 5. A single adult cedar growing out of a rocky substrate which has offered protection from the fires which have killed its neighbours.

in prescribed burns, with populations growing in the more open habitats being expected to accrue higher mortalities. Furthermore rocks appear to form the only effective barriers between cedar seedlings and mortality in even the coolest of fires. The selection of microhabitats effectively protected by rocks should thus be the main criteria upon which restoration programs involved in the planting of nursery grown seedlings are based.

The discussion thus far has not dealt with the atypical findings from Forestsum. At this site none of the four variables influenced the survival of trees during the intense wildfire experienced in November 1984. The explanation for this relates to the unusual characteristics of this particular fire. Forestsum is situated within what was, prior to the 1984 fire, the largest remaining extensive forest of *W.cedarbergensis*. It contained a very even age structure of trees in excess of 200 years old. Many of the trees at Die Bos, as this forest is locally called, are characterised by an unusual shape. They branch extensively from the base, with their lower foliage at ground level, suppressing the undergrowth (plate 6). Furthermore the forest is situated on a gentle slope with very few rocks for protection. The fire itself burnt at very high intensity (Hendricks pers. comm.) and, unusually for cedars, predominantly as a canopy fire (plate 7). This was probably a result of the shape of the trees together with their high density. Consequently the normal characteristics by which a tree survives heat scorching were ineffective and there was thus no relationship between class, or crown base height, and survival. Similarly the few rocks that were present at the site were ineffective in influencing the movement of the fire between canopies. Evidence of senescent fynbos among the islands of surviving trees at this site suggest that survival was more a function of the random spread of the fire than any characteristics of the trees themselves.

With regard the selection of sites for prescribed burning in the more typical scattered habitat of contemporary cedar populations, this study suggests that characteristics of the site and tree can be utilised in predicting the expected levels

Plate 6. A typical cedar from Die Bos (Forestsum) branching extensively from ground level. The vegetation around these trees is minimal.

Plate 7. The 1984 fire which infiltrated Die Bos devastated vast tracts of the forest. A single living tree is visible on the skyline, while a clump that was missed by the fire is visible in the right foreground.

of mortality in fire. The more protection afforded trees by rocks at a site, the lower will be the mortality in prescribed burns. Furthermore survival in cool or moderate fires requires the attainment of a basic size structure at which stage the trees bark is sufficiently well developed to survive scorching, while its height permits at least some foliage to be above the critical heat zone of the fire. Field data indicates that this basic size requirement is only reached in trees of 20 cm and more in diameter (Fig.7). A cool fire is then likely to only burn the lower foliage, leaving the more resistant upper foliage undamaged. In this way trees surviving controlled burns become more resistant to the threat of wild fires in that their living foliage is situated higher above the flames. Thus where possible controlled burns should not be carried out at sites containing cedar populations with a high proportion of the more vulnerable size classes. Juvenile dominated populations such as occurred at Panwin and Donkwin should not be burnt until the populations balance shifts towards the more tolerant size classes. In these cases it would be better to reduce the threat of wildfires by patch burning peripheral areas until the trees have grown sufficiently to provide them with a better chance of survival. There are many areas both inside and outside the cedar reserve which contain predominantly older tree classes, or lack cedars completely. It is these areas which need to be prioritized for prescribed burning in order to reduce the threat of large wild fires. This management option will be discussed further in part C of this study.

Part C. Application of a transition matrix model to explore management options for the Clanwilliam cedar.

Introduction

Matrix models are a powerful tool for investigating population dynamics. They are becoming increasingly more common as a means of investigating population processes of plants at the individual species as well as community levels (Silva etal. 1991). By incorporating data on survival, growth and fecundity for plant populations with mixed age (or stage) structures, they can be utilised to predict the future development of a population. For each stage in a plants life cycle the probability of remaining at that stage or changing to any of the others in a given time interval is calculated from observations in the field. The transition probabilities for each stage in the plants life cycle are entered into a transition matrix. The matrix is square with the same number of rows and columns representing the probability of every transition from one stage class to another (see appendix 3). By multiplying the matrix by a starting population (a vector giving the number of trees in each stage class) the population development over one time interval can be calculated. This can be represented as follows

$$A \quad X \quad n(t) \quad = \quad n(t+1)$$

where A is a population matrix, n(t) is the starting population and n(t + 1) is the population size after one time interval. With repeated multiplication of the transition matrix:

$$A \; X \; n(t) = n(t+1), \; A \; X \; n(t+1) = n(t+2), \text{ etc,}$$

the size structure of the population will stabilize at a constant ratio of stage classes. Once the stable age structure has been reached, λ (the population growth rate) can be calculated

$$\lambda = \frac{n(t + 1)}{n(t)}$$

If the eigenvalue (λ) derived for the transition probability matrix is > 1, the population should theoretically expand, whereas if this value is < 1, the population will decline. It is important to note that this approach is entirely deterministic and based on certain underlying assumptions. If these assumptions are not met, λ, as well as any predictions made by the model, will be inaccurate.

This matrix model approach was utilised by Manders (1987) to simulate the dynamics of W.cedarbergensis. In particular he wished to determine whether this species is capable of expanding its population, or whether it will become extinct regardless of attempts at conservation. He also aimed to investigate the optimum interval between fires to allow for the survival of the species.

The Model

Manders (1987) divided the cedars into eleven tree classes starting at seed through to trees with dbh of greater than 40cm (appendix 1). He made use of enumeration data which had been collated for a number of permanent plots established between 1970 - 78. Certain plots with reliable and complete data were re-enumerated during 1983 and 1984. In each plot, all individuals were labelled with numbered steel labels and diameters recorded at the first enumeration. Subsequently, individuals were re-measured and deaths due to fire and other reasons were recorded. Using this information it was possible to develop a transition count matrix for each plot and then standardize these matrices into a transition probability matrix covering a one year interval for the species (appendix 3). Using this transition matrix he calculated an eigenvalue (λ) of 1.02026, after 198 iterations (years), thus indicating that if the assumptions of the model are met, cedar populations are capable of increasing in the absence of fire.

The major shortcoming of this model relate to its predictions on mortality in fire. As mentioned earlier fire plays a major role in the dynamics of cedar populations and is the primary tool with which the species can be managed. Manders admitted that the estimation of mortality in a fire presented a considerable problem. The model assumes that mortality in fire increases with vegetation age as the fuel loads around trees increase. This was supported by the findings of Andrag (1977) and by Manders (1987) data on mortality in wildfires. A crude estimate of increasing mortality in fire with increasing vegetation age was estimated by fitting a quadratic function to three points, consisting of an arbitrary rate of 0.99 in vegetation up to 4 years old, and observed survival at 17 and 35 years. This function takes no account of varying fire intensities. Using the function to calculate mortality in fire after various time intervals, it was predicted that an interval of 15 to 20 years between successive fires would ensure the conservation of existing stands of cedars. It was concluded that, "as the bulk of the cedar habitat is of much the same age (ca. 10 years) after fire, it should be possible to collect more appropriate data in a few years time, and use the model with modified fire mortalities to make more substantive prescriptions" (Manders 1987). The devastating fire of December 1988 - January 1989, which totally destroyed vast areas of cedar habitat, burnt predominantly in vegetation of just 13 years old. This highlights the need for improving the fire mortality component in the model.

This study uses field data on cedar mortality after fires of varying intensity to simulate the impacts of fire on cedar populations. I make use of Manders (1987) transition matrix for the cedar and incorporate real post-fire mortality data from both wildfires and controlled burns to investigate various management options for the future conservation of this species.

Four aims were highlighted for the modelling component of this project;

1. To evaluate the importance of the different components of the life cycle using elasticity analysis. This will have important implications for setting management priorities.

2. To explore Manders (1987) proposed 15 - 20 year fire cycle using real post-fire mortality data. By exploring various fire cycles and fire mortality levels it is hoped that better predictions can be made with regards future management strategies for the general cedar habitat.

3. To explore the fire control requirements of the natural cedar forest (Forestsum).

4. To examine the theoretical long term predictions of implementing the proposals of the cedar reserve.

Methods

Elasticity analyses

Transition probability matrices not only provide a means of predicting the future development of a population, but can also act to measure the response in population growth rate (λ) to changes in each transition probability. It is thus feasible to examine what impact potential "mistakes" made in generating a transition will have on overall population growth rate. Manders (1987) used this technique to analyze what impact changes in the most variable transition in his model, seeds to seedlings, would have on growth rate. By reducing the proportion of seeds developing to class 2 plants by a factor of 10, he found that λ only decreased to 1.00103. From this he could conclude that even if this transition value was inaccurate, it would have little impact on the outcome of the simulation.

A technique, developed since Manders study, is the derivation of elasticity indices which calculate the relative importance of each transition in influencing population growth. Elasticity analysis provide a rapid method for calculating the proportional change in λ resulting from proportional changes in the matrix coefficients and thus quantifies the degree to which population growth is determined by the individual transition values in the matrix model. It is calculated using the equation

$$e_{ij} = \frac{a_{ij}}{\lambda} \times \frac{v_i \times w_j}{\langle v,w \rangle} .$$

where e_{ij} is the elasticity, a_{ij} is the (i,j)th element of the matrix A, and v and w are the dominant left and right eigenvectors, respectively (de Kroon etal. 1986) The derivation of the elasticity analyses from Manders cedar transition probability matrix is presented in appendix 4.

Simulations

The model

A simple program was designed, using true basic, in order to model the long term impacts of various fire regimes on cedar populations (appendix 5). Simulations of this type can be modelled using a spreadsheet package. However the large amount of data, making spreadsheet operations very slow, together with the necessity for loop operations, makes programming a more effective method. This program allows for manipulation of the starting populations of all size classes, the fire frequency, the number of fires and the degree of mortality in each fire. A flow diagram showing the major steps in the program is given in appendix 5.

Calculating mortality at a site.

For the model it was necessary to determine the proportion of trees in each size class which survived in the various fires. The proportion of trees surviving the effects of fire was calculated from random samples of approximately 200 trees at each site (see part B methods and table 2). As all tree classes have equal chance of growing in a patch which is not burnt by the fire, the overall proportion of all trees which escaped being burnt was calculated and this value added to the proportion which survived being burnt in each size class;

$$\text{eg. overall propn. of class 7 surviving at a site} = \frac{s_7}{s7 + k_7} + E$$

where s_7 is the proportion of trees in class 7 which survived the fire, k_7 is the proportion killed by the fire and E is the proportion of all the trees enumerated which survived by growing in patches within the site which were not burnt. In this way the proportion of trees in each size class which were not killed by the fire were calculated for each site (Table 2).

The value of E can be expected to decrease with the intensity of the fire. However as mentioned earlier, other factors such as vegetation type, rock cover and the patchiness of previous fires will all influence the movements of a fire front. Thus E is a highly simplified index for fire patchiness. A better understanding of factors influencing the dynamics of fire patchiness will be necessary before more accurate predictions are to be made with regards its influence at the population scale.

Combining mortalities from different sites.

Calculations in part B established that the results for the two sites which experienced low intensity fires (A and B) were very similar to each other, as were those for the two sites which experienced high intensity fires (D and E). The survival data for Panwin and Donkwin were therefore combined and the proportion of each size class surviving a low intensity fire calculated. These values were then used as survivorship rates for prescribed burns in the model. The same process was adopted with Sneeusum and Hoogsum data for high intensity burns (appendix 6).

Owing to the very poor recruitment after prescribed burns in winter, current management guidelines require that the burns should be carried out in late summer or autumn (1 January to 15 April) under conditions which minimize adult cedar mortality but ensure adequate recruitment (Anon. 1986). It was unfortunately not possible to collect field data on mortality levels for a late summer/autumn prescribed burn. The mortality figures recorded for the prescribed May 1988 fires at Panwin and Donkwin were unusually high and probably correspond quite closely with favourably selected late summer/autumn burns. However to test a worse case scenario for a late summer prescribed burn, class mortalities intermediate to those recorded for summer wildfires and winter prescribed burns were calculated (appendix 6).

The procedures used to simulate the various management options with the aid of the model.

1. <u>General cedar habitat</u>

The model was used to examine the theoretical population development of cedars growing in the general cedar habitat under various fire regimes. A number of different fire cycles were tested by running the model for the stipulated number of years between fires and then reducing the population according to the survivorship rates calculated by the method described above. The same starting population as utilised by Manders (1979 population at site A, Sneeuberg) was used for these simulations (appendix 6). Ten fire cycles were executed for all simulations, as this was found to be sufficient for determining future population trends resulting from the various management options. From the elasticity matrix it was evident that size classes 8 to 11 are the most important for population growth (see later discussion).

Thus in the figures, the effects of different fire cycles are demonstrated by their impacts on these classes by summing the number of class 8 to 11 trees alive after each fire.

1.1 Wildfires

Fire free intervals of 15, 50 and 80 years were simulated. Fifteen years was the minimum interval between fires predicted by Manders (1987) to enable cedar population to sustain themselves, and approximates the natural fire interval. The 50 and 80 year intervals are unrealistically long (unless protected). They were simulated to explore the time needed between intense wildfires if a population is to recover and expand. At each fire the number of trees in each size class were multiplied by the fraction which would be expected to survive in an intense wildfire (appendix 6).

1.2 Prescribed burns

To assess the impact of controlled winter burns as a management option, the model was run using the mortality data collected from Panwin and Donkwin (appendix 6). Simulations of 12, 15 and 20 year intervals were investigated. To test a worst case scenario for a late summer prescribed burn, the model was run for 15 and 20 year intervals with fire mortalities intermediate to those observed for summer wildfires and winter prescribed burns (appendix 6). One of the options available to managers is to clear vegetation away from around the large adult trees before burning, and thereby increase their chances of survival in prescribed burns. To examine the potential impact of this action on a worst case scenario late summer burn, the proportion of class 10 and 11 trees surviving a fire were increased to 1 (ie 100% survival) while leaving all other survival probabilities constant.

2. Die Bos

In order to gain some insight into the management strategy required to conserve the forest at Die Bos, the mortality figures from the 1985 fire at this site (appendix 6) were incorporated into the matrix model and various fire intervals examined. The starting population is given in appendix 6 and was calculated from a survey of approximately 1 Ha of part of the existing (1994) population at the site. The number of seeds (class 1) was calculated by multiplying trees in the seed producing classes by their average annual seed production calculated by Manders (1987). The model was run for ten fires at an interval of 15, 40 and 50 years between fires.

3 The cedar reserve

Management guidelines for the cedar reserve require low intensity patch burning at a three to four year cycle in late autumn/early winter (van der Merwe and Wessels 1993). Both Panwin and Donkwin were burnt for the first time as part of this program, resulting in high mortality in all except the largest tree classes. It is to be expected that mortality will be higher in the initial fire, as the surrounding vegetation in most of the cedar reserve is in excess of forty years old (Hendricks pers. comm.) (plate 8). A second fire after only four years is unlikely to burn the same area, instead burning patches missed by the previous fire. Thus a more realistic simulation of what might be expected in the cedar reserve is an initial fire resulting in high mortality, followed by lower mortalities in fires with an 8 year interval. Management guidelines also require that nursery-reared seedlings be planted out after fires to booster recruitment. It has been proposed that the reserve be divided into four blocks and that planting be carried out sequentially in one block a year (Privett Unpublished report). This will mean that seedlings are planted at the same site at a minimum period of four years apart. However seedlings are only planted after an area is burnt and thus, for simplicity, plantings in the model was confined to the year after each prescribed burn. Although it was originally proposed that a target density of 1000 seedlings per hectare be aimed for (van der Merwe and Wessels 1993), a shortage of suitable microhabitats means that this figure is probably closer to 500 seedlings per hectare in reality. Two hypothetical scenarios for managing the cedar reserve according to the required guidelines can be simulated using the model.

* In those instances where cedar stands already exist.
* In those situations where no cedars are present.

3.1. Starting population of adult cedars.

The pre-fire populations at Donkwin and Panwin were combined and utilised as the starting population (appendix 6). In order to stimulate the planting out of nursery reared seedlings, a value of 500 was added to class two after every fire. The model was adapted to incorporate the initial high mortality as measured at Panwin and Donkwin, followed by reduced mortality in fires at a eight year cycle. As no secondary prescribed burns have as yet been carried out in the reserve, an arbitrary 20% increase in survival was added on to the figures derived from the initial winter burns at sites A and B (appendix 6). Although this value is purely subjective, it is, if anything, likely to be an underestimate of fire survival in eight year old vegetation. To test the importance of planting seedlings, the model was also run without the addition of any class 2 individuals after fires.

3.2 Sites with no living cedars

Many suitable cedar habitats within the reserve contain no, or very few, living trees. It is been considered by management to burn and plant these areas first, before disturbing the existing stands of trees (Wessels pers. comm.). The model was thus run with a starting population of 1000 class two seedlings and no other trees. In order to examine the time needed for seedlings to reach the more fire resistant size classes, the model was initially run without fires for 100 years. The model was also used to simulate the impacts on a starting population of seedlings of an eight year fire cycle with and without the addition of 500 seedlings after each fire.

Results

Elasticity analysis.

	1	2	3	4	5	6	7	8	9	10	11
1	0	0	0	0	0	2.7E-05	0.00127	0.00076	0.00223	0.00325	0.00821
2	0.01574	0.04218	0	0	0	0	0	0	0	0	0
3	0	0.0139	0.02827	0	0	0	0	0	0	0	0
4	0	0.00184	0.01013	0.02465	0	0	0	0	0	0	0
5	0	0	0.00137	0.0052	0.01828	0	0	0	0	0	0
6	0	0	0.00241	0.00338	0.00328	0.00892	0	0	0	0	0
7	0	0	0	0.00034	0.00033	0.0009	0.00698	0	0	0	0
8	0	0	0	0	0	0	0.00977	0.10381	0	0	0
9	0	0	0	0	0	0	0.00467	0.00902	0.14574	0	0
10	0	0	0	0	0	0	0	0	0.01146	0.15272	0
11	0	0	0	0	0	0	0	0	0	0.00821	0.35111

Table 10. Elasticity analysis for *W.cedarbergensis* derived from the transition probability matrix of Manders in appendix 3.

The elasticity indices provides information about the extent to which population growth depends on survival, growth, and reproduction at different stages in the life cycle (Caswell 1989). It is thus evident that size classes 8-11 make the largest contribution to population growth, whereas the smaller size classes contribute very little. Together these three largest classes have a proportional contribution of 75.3% of the total elasticity of the life cycle, while no other size class contributes more than 5%.

Simulations

1. General cedar habitat

1.1 Wildfires

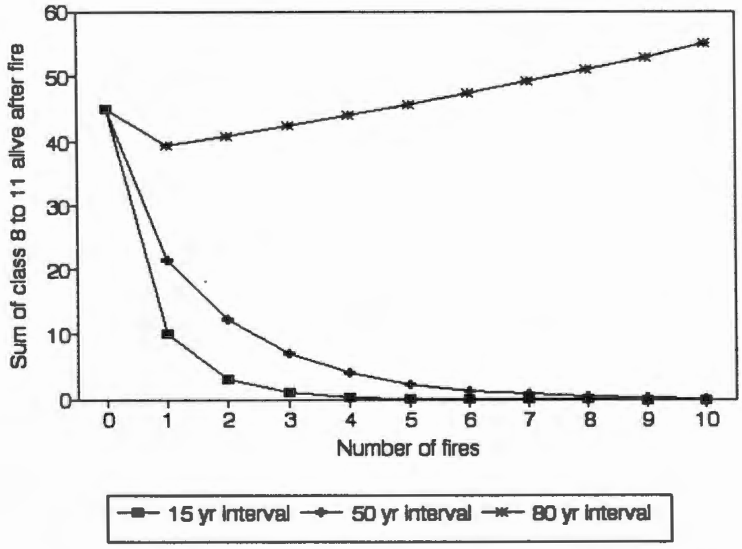

Fig. 8. The development of a cedar population subjected to intense wildfires at various intervals.

The population rapidly declines to extinction in both the 15 and 50 year interval simulations. It is only once the interval between intense fires is extended to 80 years that the population can be expected to increase slightly.

1.2 Prescribed burns

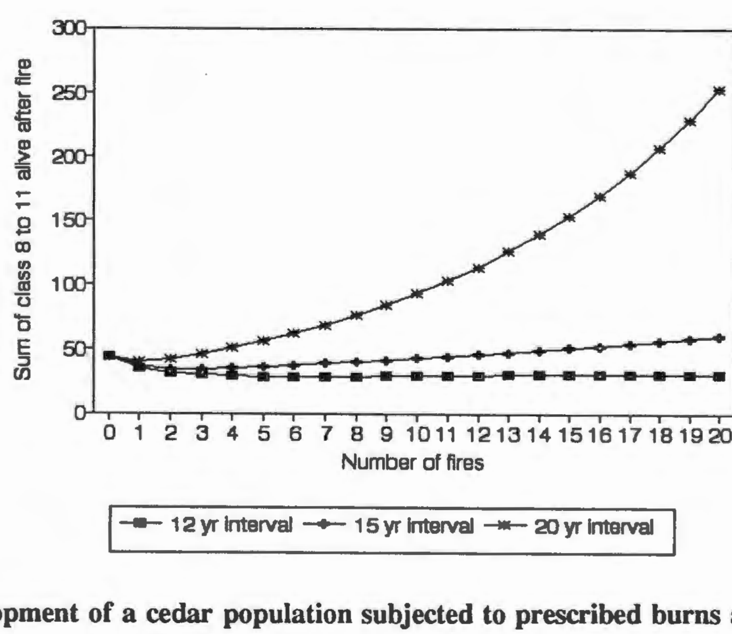

Fig. 9. The development of a cedar population subjected to prescribed burns at various intervals.

At all three intervals there is an initial decrease in the sum of classes 8 to 11 followed by varying degrees of population expansion. The population remains virtually stable with a 12 year interval, increases very slightly with a 15 year interval and increases rapidly with a 20 year interval between prescribed burns.

Worst case scenario prescribed burns.

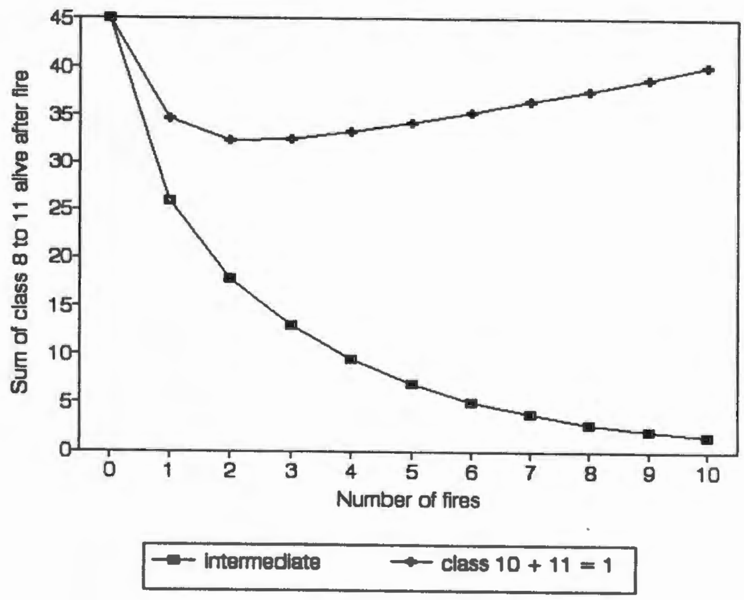

Fig. 10. **The theoretical development of a population of cedars subjected to a worst case scenario prescribed burn (i.e. mortality is intermediate between that recorded for the wildfires and the prescribed burns) on a twenty year cycle. (The upper curve represents a population in which all class 10 and 11 trees survive the fires).**

At both fifteen and twenty year intervals the model predicts that the population will decline rapidly (fifteen year interval not included in graph). However by reducing the mortality of classes 10 and 11 to a value of zero, while keeping all other mortality values constant, the population, after initially decreasing, will increase if exposed to a twenty year interval between fires.

2. Future management of Die Bos

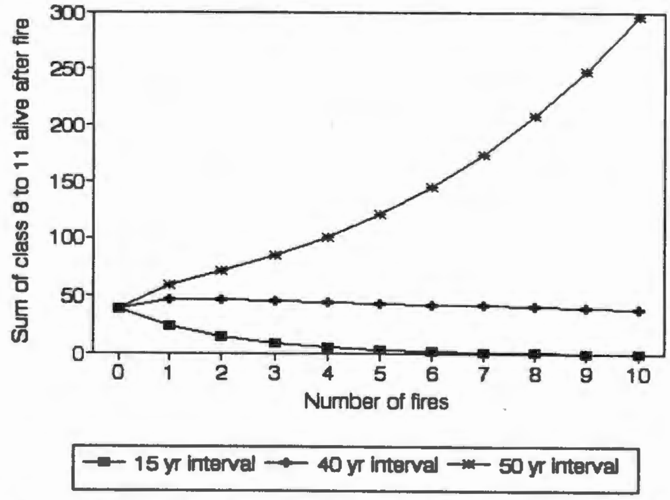

Fig. 11. Theoretical population development at Forestsum Bos under alternative fire intervals.

On the basis of the model, the population at Forestsum will decline rapidly towards extinction if exposed to a fifteen year fire interval. It is predicted that a fire interval of forty-two years is the minimum timespan required to enable a long-term positive growth rate for this population. A fifty year interval between fires will ensure ~~in~~ a steady increase in population size.

3. Management of the cedar reserve.

3.1 Starting population of cedars

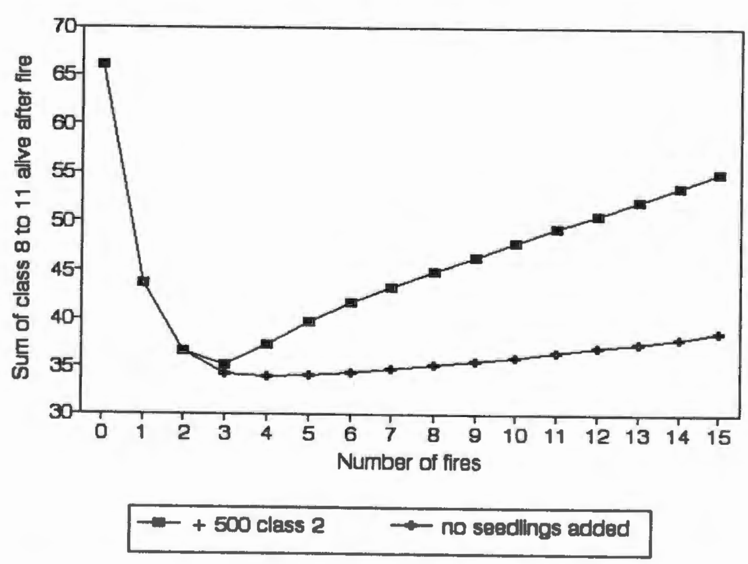

Fig. 12. **Theoretical development of a population of cedars in the cedar reserve exposed to an 8 year fire interval, with and without the addition of 500 seedlings after each fire.**

The model predicts that the initial fire has a major impact on the population. However the population is able to gradually recover under the reduced mortality levels of fires burning in eight year old vegetation. The addition of 500 seedlings after each fire results in a much more rapid increase in population development.

3.2 Sites with no living natural cedars

When the model was run with a starting population of 1000 seedlings and no fires, 47 classes 8 - 11 became established in 100 years. The model predicted that it would take at least 30 years for class 2 individuals to reach a DBH of 20 cm. In the absence of fire the population growth rate λ stabilizes at 1.020299 after 233 years.

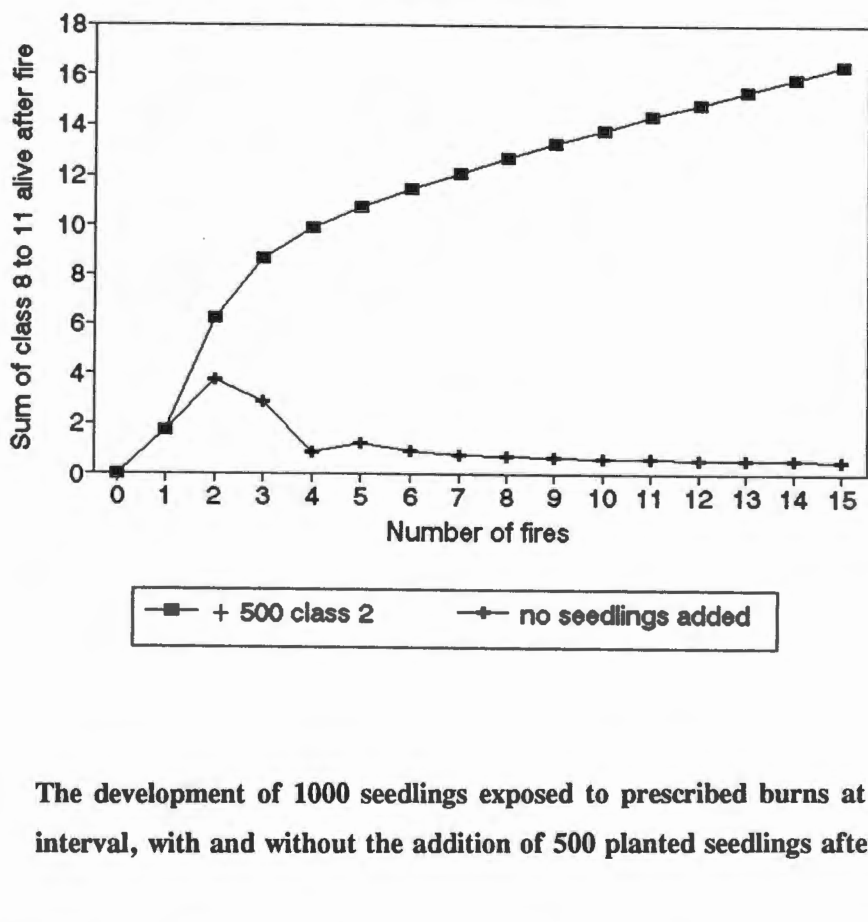

Fig. 13. **The development of 1000 seedlings exposed to prescribed burns at an 8 year fire interval, with and without the addition of 500 planted seedlings after each fire.**

When no post-fire seedlings were planted the population was unable to establish. The addition of 500 seedlings after each fire enabled the population to expand.

Discussion

Elasticity analysis

The results of the elasticity analysis emphasises the importance of the larger size class trees for cedar conservation, as it is their survival/transition which contributes most to population growth. Mortality in these size classes will most strongly influence the future survival of cedar populations. This highlights the necessity of conserving the larger size classes in fires and thus supports the objectives of the cedar reserve. Much of the emphasis of recent cedar research and management has been directed towards ensuring adequate postfire regeneration (Manders and Botha 1989, Mustart etal. in press). While not discounting the importance of this aspect, any management action which leads to the death or damage of adult trees will be having a major negative impact on the status of this species. As an example, the Panwin site in the cedar reserve was burnt in prescribed fire and subsequently planted with seedlings. However the fire was unexpectedly intense, killing or damaging the majority of reproductively active trees, while the majority of seedlings planted have since died (pers obs.). Thus despite the good intentions of management, a healthy and viable population before human intervention has been severely and possibly irreversibly impacted by injudicious fire management.

The value of the adult trees in contributing to population growth also provides evidence for the immense impact that wood cutters must have had on cedar populations. By selecting only the most healthy adult trees for felling, they removed the crucial components of population growth. With every adult tree removed, population fecundity was proportionally reduced, and the impacts of later fires would have become all the more devastating.

General cedar area

Summer wildfires such as occurred in 1988/89 have a devastating impact on cedar populations. Given the importance of the large size classes to population development, it is the high levels of damage and death of these trees in wildfires which has the greatest impact on the future of the population. It is evident that if the high intensity wildfires such as occurred on the Sneeuberg range in 1975 and 1988/9 continue to occur at a similar interval in the future, the population will rapidly decline towards extinction. The model predicts that a fire free interval of 80 years is required if the population is to remain viable. However in the general cedar habitat, management has to be directed toward the maintenance of species diversity (Kruger and Bigalke 1984, van der Merwe and Wessels 1993) which according to Bond (1980) and van Wilgen (1981) requires a fire interval of between 12 and 20 years. Furthermore the fire history of the Cedarberg mountains for the period 1956-1986 showed an average frequency of 11-15 years between fires (Brown etal. 1991). The only viable option is thus to pre-empt intense wildfires, by implementing prescribed burns under more favourable conditions within the required fire cycle.

The major advantage of prescribed burns under cool favourable conditions is that they have little impact on the largest size classes (fig.7) Evidence from the field also suggests that the cooler fires tend to burn more patchily, thereby allowing more trees to escape damage. As evident from the simulations, these factors combine to reduce the impact of the fire and enable cedar populations to recover between fires. Even under the most severe prescribed burns (as simulated with the intermediate fire mortalities), the model predicts that at a 20 year interval cedar populations will expand if the two largest size classes are protected from fire. This once again illustrates the importance of the larger size classes and thus the need to prevent mortality of these classes in prescribed burns.

The idea behind using prescribed burns is to preempt large devastating wildfires. It is therefore necessary to make the interval between fires as short as possible while not having a detrimental impact on cedar populations. The model predicts that a fire cycle of 15 to 20 years will ensure that the population expands, while an interval of 12 years will result in the population remaining virtually constant. This presents a major dilemma to managers, as an interval as short as thirteen years can, as was the case with the 1988/89 fire, result in devastating wild fires. Thus the decision has to be made as to whether to leave a block for 15 - 20 year interval and thereby ensure adequate post fire recovery while running the risk of the increased threat of wild fires, or to burn after a 10 - 11 year interval, preempting wildfires, but reducing population size. A possible solution may lie in selecting low cedar density areas for the shorter interval burns to reduce the overall threat of wild fire threat, while leaving the more populous cedar sites for the longer intervals.

Regardless of the precise interval adopted, the essential criteria is to reduce flammability on the landscape scale by breaking the vegetation up into different aged compartments. The present uniformity of vegetation age structure (6-10 yrs) over the majority of the cedars distribution is once again posing the threat of a large scale wildfire within the next decade.

Die Bos

The forest at Die Bos provides management with a major conservation challenge. It also provides scientists with valuable clues as to how cedars have declined to their present status. A variety of sources have argued, with little evidence, for the theory that cedars were much more abundant in the past, and that their dense stands suppressed undergrowth, thereby increasing resistance to fires (Van der Byl 1895). The 1985 fire which burnt the extensive closed canopy forest at Die Bos provides an excellent opportunity for further investigating this hypothesis. The fire burnt under extremely dry and windy conditions, and moved rapidly through the forest (Hendrickse pers.com). However despite the devastated appearance of the forest, closer inspection reveals some interesting facts. Although only 14% of the trees growing in the fire's path survived, a further 30% of the trees sampled survived as a result of the fires patchiness (table 2). It is therefore probable that although these large forests would burn, they would do so only under the most intense conditions. Under these conditions the fire moves rapidly through the canopy bypassing certain tracts of the forest.

Post fire regeneration at Die Bos ranged from very good to virtually non-existent. The post fire recruits are now over 1 metre tall and well established (plate 9). A survey on the upper northern boundary of the forest revealed virtually no visible recruitment. Although there were reports of severe seedling mortality due to livestock browsing after the fire (Bands 1986), a more likely explanation for this lack of recruitment was the intensity of the fire in this area. This is evident from the many trees which were burnt to the ground as well as the large scale soil erosion which has exposed tree roots. The fire appears to have burnt less intensely through the rest of the forest and consequently post-fire recruitment was much better in these areas. A survey of approximately 100 m^2 above the Agtertafelberg footpath revealed a sapling to adult ratio of 7.9:1 (435 saplings: 55 adults). A similar ratio was obtained from a survey of the recruitment of seedlings after a fire in the planted forest at De Rif. Recruitment from closed canopy forests can be expected to be far superior to that in more scattered populations, both as a result of greater seed loads and better microhabitats for seedling development.

It can thus be hypothesised that large cedar groves were able to suppress undergrowth and thereby prevent all but the most intense fires from infiltrating them. These intense fires were probably seperated by long fire free intervals, as was the case at Die Bos, allowing the population to reach maturity and expand between fires. Even the occurrence of these very intense fires would probably have left some portions of the population undamaged. Except under the most intense conditions, post-fire regeneration in the burnt areas would have been very good, while the unburnt patches would have further supplemented population recovery.

While not suggesting that the Cedarberg was ever covered with a blanket of cedars, evidence from this site suggests that similar large groves might well have occurred at other favourable localities within the range. An increase in fire occurrence relating to human activities, together with the influence of woodcutters could thus explain the demise of these cedar groves. It is apparent from Die Bos that large areas covered by dense trees prior to the fire, and which showed no post-fire recruitment, are

Plate 8. Dense restio-veld such as this is typical over much of the cedar reserve. The young cedars at this site will almost certainly be killed in a prescribed fire.

Plate 9. Regeneration at Die Bos 9 years after the fire. Trees in this area were killed by a canopy fire as is evident by the tall individual on the left.

already covered in typical Cedarberg fynbos. A further fire before recruits reach maturity, and this once great population will have been reduced to a few scattered trees inside the space of twenty years.

Thus as would have been the case in the cedar groves of the past, the biggest threat to Die Bos is the occurrence of another fire before the recruits have matured and established a large enough seed bank. The model predicts that a fifty year interval is the minimum protection period that management should aim for to conserve Die Bos. The current status of the forest, with its many dead trees and young saplings, makes it particularly susceptible to wild fires which occur naturally at a frequency of about 15 years. It will thus be necessary for management to embark on a proactive fire protection program for this population if this unique remnant of cedar heritage is to be conserved.

Cedar Reserve

At this stage it is difficult to simulate the proposed management guidelines for the cedar reserve as no sites have been patch burnt twice, and none of the planted sites have been re-burnt. However if the assumptions of the model are met, an existing population of cedars, supplemented with seedlings after each fire, can be expected to increase with an eight year interval between prescribed burns. Even if no post-fire seedlings are added, the model predicts that given the expected lower mortality in secondary fires, populations of cedars will gradually expand. The addition of the nursery-reared seedlings does however lead to a marked improvement in the rate of the recovery of the population, and is thus an important component of the program.

There are many areas of suitable cedar habitat within the Cedar Reserve which contain no, or very few, trees. It is primarily these areas which have up until now been selected for burning and planting of cedars. A starting population of 1000 class 2 individuals burnt on an 8 year rotation result in the rapid decline of the population unless it is continuously bolstered by more seedlings after each fire. The mortality of planted seedlings in fire is one of the major concerns of management in the reserve. Thus far no planted sites have been re-burnt owing to concern for the expected high mortality of the artificial regenerates. It makes no sense to go to the considerable effort of growing and planting seedlings only to kill them in their first prescribed burn. However attempts to protect them from fire until they reach maturity and thus become more fire resistant opposes the policy of maintaining young vegetation in the reserve.

It is therefore most important that seedlings are only planted in very fire protected microsites. If the site is then burnt and the seedlings die, it is evidence that those sites are unsuitable and should not be re-planted. Another option is to avoid burning recently planted sites. By patch burning the many unplanted areas in the reserve it will still be possible to reduce the overall fire threat considerably, and at the same time allow the artificial regenerates to become better established. According to the model a minimum fire free period of approximately thirty years is necessary to enable seedlings to reach the 20 cm diameter required for adequate protection against prescribed burns. The decision as to whether planted sites should be burnt at an eight year interval, or left until they reach maturity, can only be made once some trial plots are burnt and mortalities of planted seedlings measured.

As was the case with the general cedar habitat, the aspect crucial to the success of the reserve will be to minimize the loss of larger size class trees in fires. The model's prediction of increasing populations at an eight year interval is dependent on the high level of survival in prescribed burns. These can only be achieved by burning under optimum conditions. Furthermore those sites with few or no adult cedars should be prioritized for initial burning. As a further precaution, the few large trees at these sites could have the vegetation cleared away from underneath them. Thus the model predicts that if mortality in fire can be kept low enough to ensure adequate survival of trees (especially in the larger size classes), populations of cedars will expand under the current management guidelines for the reserve.

GENERAL DISCUSSION

This study has highlighted the importance of conserving the larger size class trees in cedar management. The four largest size classes provide the major contribution to population growth and should thus be granted the main conservation status. Owing to the high mortality in these classes during intense wildfires, a continuance of fires such as occurred in the Sneeuberg range in 1975 and 1988 could result in the extinction of the Clanwilliam cedar over much of its distribution range. It is thus essential that the threat of wildfires be reduced by prescribed burning both inside and outside the cedar reserve. In areas containing cedars, the most important aspect of these prescribed burns is that they be performed under optimum conditions allowing for both adult survival and adequate post-fire regeneration. The findings of this study suggest that the sensitivity of cedar foliage to scorching changes with season, and consequently decisions as to when to burn should take this into account. However the importance of this characteristic needs to be further explored and a correlative test for determining the best time to burn derived. At this stage the present strategy of burning in late summer/early spring after the first rains would appear to be the most appropriate.

To enable populations to persist in the general cedar area requires as much time as possible between fires to enable the population to develop many large seed producing trees and thereby ensure adequate post fire recruitment. However at the same time prescribed burns are necessary to reduce the threat of wildfires. It is therefore proposed that the interval between prescribed burns should range from 10 to 20 years at the discretion of the manager, with the cedar rich compartments being allocated the longest intervals. Where feasible, populations with a large juvenile component should not be burnt until they have reached a more fire tolerant size (preferably 20cm DBH). The establishment of the cedar reserve should not mean that populations outside the reserve are neglected. Careful fire management which reduces the threat of large wildfires, but at the same time conserves biodiversity, is required. Furthermore artificial regeneration need not be confined solely to the reserve. There are many easily accessible populations which showed minimal regeneration after the 1988 fire that could be bolstered by seedling planting.

The future of the large cedar forest along the Agtertafelberg footpath (Die Bos) is threatened by further wildfires. Owing to the uniqueness of this population it is suggested that some form of proactive fire prevention strategy be instigated at this site. Die Bos needs at least a further forty years of protection to allow for adequate recovery from the last fire.

The selection of sites to burn in the cedar reserve needs to take cognisance of the number of cedars present, their size and the degree of protection afforded by rocks. Ideally the best sites for patch burning are those with the lowest density of cedars (preferably large size classes) and with a very rocky terrain. Owing to the age of the vegetation in much of the cedar reserve, it is important for the conservation of existing populations that prescribed burns are only administered under optimal conditions. Populations with a large proportion of the more vulnerable size classes can be expected to show high mortality and where possible should not be burnt. The most important component of the seedling transplant program is that seedlings are only planted in habitats well protected from fire. Although mortality in prescribed burns of planted seedlings requires investigation, it may be preferable if the planted sites are not burnt for up to thirty years after planting to allow for individuals to become more tolerant to fires. This will require that areas peripheral to planted sites are regularly burnt to reduced the risk of wildfires.

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APPENDIX 1. **Categories used for the classification of cedars by height and diameter for the transition count matrices. (after Manders 1987)**

Definition	Class
Seed	1
Seedling < 25cm high	2
Plants > 25 cm and < 50 cm high	3
Plants > 50 cm and < 75 cm high	4
Plants > 75 cm and < 100 cm high	5
Plants > 100 cm and < 150 cm high	6
Trees > 150 cm high with dia. < 5 cm	7
Trees > 5 cm dia. and < 10 cm dia.	8
Trees > 10 cm dia and < 20 cm dia.	9
Trees > 20 cm dia and < 40 cm dia.	10
Trees > 40 cm dia.	11

Appendix 2 **The results of the GLIM analysis.**

GLIM ANALYSIS OF COMBINED PANWIN AND DONKWIN DATA.

```
 [o]  GLIM  3.77 update  0  (copyright)1985  Royal  Statistical
Society, London
 [o]
 [i] ? $units 39$
 [i] ? $data clas shap folh rock inte aliv not$
 [i] ? $read
 [i] $REA? 1 1 1 1 1 3 16
 [i] $REA? 1 1 1 1 2 0 33
 [i] $REA? 1 1 1 1 3 0 12
 [i] $REA? 1 1 1 1 4 0 1
 [i] $REA? 1 1 1 2 1 2 6
 [i] $REA? 1 1 1 2 2 0 9
 [i] $REA? 1 1 1 3 3 0 1
 [i] $REA? 1 1 1 4 1 1 0
 [i] $REA? 1 2 1 1 2 0 1
 [i] $REA? 2 1 1 1 1 07
 [i] $REA? $read
 [f] ** not a real number, at [$REA? $]
 [f]
 [h] A real number was expected for the $REA  directive but was
not present.  The
 [h]  current line  width is  80 -  is this  sufficient for all
numbers to be read.
 [h] Re-enter the complete directive.
 [h]
 [i] ? $units 39$
 [w] -- model re-initialised
 [i] ? $data clas shap folh rock inte aliv not$
 [i] ? $read
 [i] $REA? 1 1 1 1 1 3 16
 [i] $REA? 1 1 1 1 2 0 33
 [i] $REA? 1 1 1 1 3 0 12
 [i] $REA? 1 1 1 1 4 0 1
 [i] $REA? 1 1 1 2 1 2 6
 [i] $REA? 1 1 1 2 2 0 9
 [i] $REA? 1 1 1 3 3 0 1
 [i] $REA? 1 1 1 4 1 1 0
 [i] $REA? 1 2 1 1 2 0 1
 [i] $REA? 2 1 1 1 1 0 7
 [i] $REA? 2 1 1 1 2 0 10
 [i] $REA? 2 1 1 1 3 0 5
 [i] $REA? 2 1 1 2 1 4 4
 [i] $REA? 2 1 1 2 2 0 7
 [i] $REA? 2 1 1 2 3 0 1
 [i] $REA? 2 1 1 3 1 2 1
 [i] $REA? 2 1 1 3 2 1 2
 [i] $REA? 2 1 1 3 3 0 2
 [i] $REA? 2 1 1 4 1 1 0
 [i] $REA? 2 2 1 1 1 1 1
 [i] $REA? 2 2 1 2 2 0 1
 [i] $REA? 2 2 2 1 1 1 0
 [i] $REA? 2 2 2 3 1 1 0
 [i] $REA? 3 2 2 3 2 0 1
 [i] $REA? 2 2 3 3 1 0 1
 [i] $REA? 2 2 4 1 1 1 0
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 [i] $REA? 3 1 1 3 1 1 0
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 [i] $REA? 3 2 2 3 2 1 0
 [i] $REA? 3 2 2 4 2 1 0
 [i] $REA? 3 2 3 3 2 1 0
 [i] $REA? 3 2 4 4 1 1 0
 [i] $REA? 3 4 1 1 2 1 0
 [i] $REA? 3 4 3 3 1 2 0
 [i] $REA? 3 4 3 3 2 5 0$
 [i] ? $calc x=live + not$
 [f] ** undefined or deleted identifier, at [ive + not$]
 [f]
 [h]  The  identifier  LIVE  used  in  the  $CAL  directive  is
undefined, possibly because
 [h] it  was previously  deleted.  Its  type is not  defined by
its present usage.
 [h]
 [i] ? $calc x=aliv + not$
 [i] ? $fac clas 3 shap 4 folh 4 rock 4 inte 4$
 [i] ? $yvar live$
 [i] ? $error b x$
 [i] ? $link g$
 [i] ? $display m$
 [o] Current model:
 [o]
 [o]   number of units is  39
 [o]
 [o]   y-variate  LIVE
 [o]   weight     *
 [o]   offset     *
 [o]
 [o]   probability distribution is BINOMIAL
 [o]     with binomial denominator X
 [o]              link function is LOGIT
 [o]            scale parameter is 1.000
 [o]
 [o]   terms =  1
 [o]
 [i] ? $yvar aliv$
 [i] ? $error b x$
 [i] ? $link g$
 [i] ? $display m$
 [o] Current model:
 [o]
 [o]   number of units is  39
 [o]
 [o]   y-variate  ALIV
 [o]   weight     *
 [o]   offset     *
 [o]
 [o]   probability distribution is BINOMIAL
 [o]     with binomial denominator X
 [o]              link function is LOGIT
 [o]            scale parameter is 1.000
 [o]
 [o]   terms =  1
 [o]
```

```
[i] ? $fit $
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[i] ? $look %x2 %df$
[o]     117.6   38.00
[i] ? $fit :+clas +shap +folh +rock +inte$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[o] scaled deviance = 19.536 (change = -111.66) at cycle 10
[o]               d.f. = 25      (change =  -13    )
[o]      (no convergence yet)
[o]
[i] ? $look %x2 %df$
[o]    53.13   25.00
[i] ? $fit :+clas + shap + folh +rock$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[o] scaled deviance = 41.118 (change =  -90.08) at cycle 10
[o]               d.f. = 28      (change =  -10    )
[o]
[i] ? $look %x2 %df$
[o]    101.1   28.00
[i] ? $fit :+clas + shap +folh + inte$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[o] scaled deviance = 28.990 (change = -102.21) at cycle 10
[o]               d.f. = 28      (change =  -10    )
[o]
[i] ? $look %x2 %df$
[o]    40.45   28.00
[i] ? $fit :+clas + shap + rock + inte$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[o] scaled deviance = 23.373 (change = -107.83) at cycle 10
[o]               d.f. = 28      (change =  -10    )
[o]
[i] ? $look %x2 %df$
[o]    33.26   28.00
[i] ? $fit :+clas + folh + rock + inte$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[w] -- unit 36 held at limit
[o] scaled deviance = 21.680 (change = -109.52) at cycle 10
[o]               d.f. = 27      (change =  -11    )
[o]
[i] ? $look %x2 %df$
[o]    69.20   27.00
[i] ? $fit :+shap + folh + rock + inte$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[o] scaled deviance = 32.780 (change =  -98.42) at cycle 10
```

```
[o]               d.f. = 27      (change =  -11    )
[o]
[i] ? $look %x2 %df$
[o]     65.27   27.00
[i] ? $fit :inte$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[o] scaled deviance = 110.49 at cycle  7
[o]               d.f. =  35
[o]
[i] ? $fit :+inte$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[o] scaled deviance = 110.49 (change =  -20.71) at cycle  7
[o]               d.f. =  35     (change =   -3    )
[o]
[i] ? $look %x2 %df$
[o]    104.7   35.00
[i] ? $fit :+rock$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[o] scaled deviance = 77.659 (change =  -53.54) at cycle  8
[o]               d.f. = 35      (change =   -3    )
[o]
[i] ? $look %x2 %df$
[o]    91.10   35.00
[i] ? $fit :+folh$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[o] scaled deviance = 76.808 (change =  -54.39) at cycle  7
[o]               d.f. = 35      (change =   -3    )
[o]
[i] ? $look %x2 %df$
[o]    92.40   35.00
[i] ? $fit :shap$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
[o] scaled deviance =  86.70 at cycle  8
[o]               d.f. =  36
[o]
[i] ? $fit :+shap$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o] scaled deviance = 88.70 (change =  -42.50) at cycle  8
[o]
[i] ? $look %x2 %df$
[o]    91.64   36.00
[i] ? $fit :+clas$
[o] scaled deviance = 131.20 at cycle  3
[o]               d.f. =  38
[o]
```

GLIM ANALYSIS OF FORESTSUM DATA.

```
[o] GLIM  3.77 update  0  (copyright)1985  Royal  Statistical
Society, London
[o]
[i] ? $UNITS 25$
[i] ? $DATA CLAS SHAP FOLH ROCK ALIV NOT$
[i] ? $READ
[i] $REA? 1 3 1 3 0 1
[i] $REA? 2 1 1 1 3 5
[i] $REA? 2 1 1 2 0 4
[i] $REA? 2 1 2 1 1 1
[i] $REA? 2 1 2 2 0 1
[i] $REA? 2 2 1 1 1 4
[i] $REA? 2 2 3 1 1 1
[i] $REA? 2 2 3 2 0 1
[i] $REA? 2 3 1 1 2 1
[i] $REA? 2 3 2 1 1 0
[i] $REA? 2 4 3 1 1 0
[i] $REA? 3 1 1 1 2 0
[i] $REA? 3 1 2 10 1
[i] $REA? $PRINT READ$
[f] ** not a real number, at [$REA? $]
[f]
[h] A real  number was expected for the $REA directive but was
not present.  The
[h] current  line width  is 80 -  is this  sufficient for  all
numbers to be read.
[h] Re-enter the complete directive.
[h]
[i] ? $READ
[i] $REA? 1 3 1 3 0 1
[i] $REA? 2 1 1 1 3 5
[i] $REA? 2 1 1 2 0 4
[i] $REA? 2 1 2 1 1 1
[i] $REA? 2 1 2 2 0 1
[i] $REA? 2 2 1 1 1 4
[i] $REA? 2 2 3 1 1 1
[i] $REA? 2 2 3 2 0 1
[i] $REA? 2 3 1 1 2 1
[i] $REA? 2 3 2 1 1 0
[i] $REA? 2 4 3 1 1 0
[i] $REA? 3 1 1 1 2 0
[i] $REA? 3 1 2 1 0 1
[i] $REA? 3 2 1 1 7 6
[i] $REA? 3 2 1 3 2 2
[i] $REA? 3 2 2 1 1 5
[i] $REA? 3 2 2 3 1 1
[i] $REA? 3 2 3 1 0 1
[i] $REA? 3 2 4 1 1 1
[i] $REA? 3 3 1 1 8 4
[i] $REA? 3 3 1 2 1 0
[i] $REA? 3 3 1 3 2 1
[i] $REA? 3 3 2 1 1 0
[i] $REA? 3 3 2 2 1 0
[i] $REA? 3 3 4 3 0 1
[i] ? $CALC X=ALIV+NOT$
[i] ? $FAC CLAS 3 SHAP 4 FOLH 4 ROCK 4$
[i] ? $YVAR ALIV$
[i] ? $ERROR B X$
```

```
[i] ? $LINK G$
[i] ? $DISPLAY M$
[o] Current model:
[o]
[o]   number of units is  25
[o]
[o]   y-variate  ALIV
[o]   weight     *
[o]   offset     *
[o]
[o]   probability distribution is BINOMIAL
[o]     with binomial denominator X
[o]              link function is LOGIT
[o]            scale parameter is 1.000
[o]
[o]   terms =  1
[o]
[i] ? $FIT $
[o] scaled deviance = 30.710 at cycle  4
[o]             d.f. = 24
[o]
[i] ? $FIT :+CLAS$
[o] scaled deviance = 30.710 at cycle  4
[o]             d.f. = 24
[o]
[o] scaled deviance = 27.003 (change = -3.7068) at cycle  6
[o]             d.f. = 22     (change = -2      )
[o]
[i] ? $LOOK %X2 %DF$
[o]    21.26   22.00
[i] ? $FIT :+SHAP$
[o] scaled deviance = 30.710 at cycle  4
[o]             d.f. = 24
[o]
[o] scaled deviance = 23.091 (change = -7.6190) at cycle  8
[o]             d.f. = 21     (change = -3      )
[o]
[i] ? $LOOK %X2 %DF$
[o]    18.33   21.00
[i] ? $FIT :+FOLH$
[o] scaled deviance = 30.710 at cycle  4
[o]             d.f. = 24
[o]
[o] scaled deviance = 29.881 (change =  -0.829) at cycle  4
[o]             d.f. = 21     (change =  -3     )
[o]
[i] ? $LOOK %X2 %DF$
[o]    23.40   21.00
[i] ? $FIT :+ROCK$
[o] scaled deviance = 30.710 at cycle  4
[o]             d.f. = 24
[o]
[o] scaled deviance = 28.843 (change =  -1.867) at cycle  4
[o]             d.f. = 22     (change =  -2     )
[o]
[i] ? $LOOK %X2 %DF$
[o]    23.94   22.00
[i] ? $FIT :+CLAS + SHAP + FOLH + ROCK$
```

```
[o] scaled deviance = 30.710 at cycle  4
[o]            d.f. = 24
[o]
[o] scaled deviance = 17.324 (change = -13.386) at cycle  8
[o]            d.f. = 14     (change = -10     )
[o]
[i] ? $FIT :+CLAS + SHAP + FOLH$
[o] scaled deviance = 30.710 at cycle  4
[o]            d.f. = 24
[o]
[o] scaled deviance = 18.529 (change = -12.181) at cycle  8
[o]            d.f. = 16     (change =  -8     )
[o]
[i] ? $FIT :+CLAS +SHAP +ROCK$
[o] scaled deviance = 30.710 at cycle  4
[o]            d.f. = 24
[o]
[o] scaled deviance = 18.131 (change = -12.579) at cycle  8
[o]            d.f. = 17     (change =  -7     )
[o]
[i] ? $FIT :CLAS +FOLH +ROCK$
[o] scaled deviance = 30.710 at cycle  4
[o]            d.f. = 24
[o]
[o] scaled deviance = 24.639 at cycle  6
[o]            d.f. = 17
[o]
[i] ? $FIT :+CLAS + FOLH + ROCK$
[o] scaled deviance = 30.710 at cycle  4
[o]            d.f. = 24
[o]
[o] scaled deviance = 24.639 (change =  -6.071) at cycle  6
[o]            d.f. = 17     (change =  -7     )
[o]
[i] ? $FIT :+SHAP + FOLH + ROCK$
[o] scaled deviance = 30.710 at cycle  4
[o]            d.f. = 24
[o]
[o] scaled deviance = 20.715 (change =  -9.995) at cycle  8
[o]            d.f. = 16     (change =  -8     )
[o]
[i] ? $STOP$
```

GLIM ANALYSIS OF COMBINED SNEEUSUM AND HOOGSUM DATA.

```
 [o]  GLIM  3.77 update  0  (copyright)1985  Royal  Statistical
Society, London
 [o]
 [i] ? $units 52$
 [i] ? $data clas shap folh rock aliv not$
 [i] ? $read
 [i] $REA? 111101
 [f] ** integer or number too large, at [EA? 111101]
 [f]
 [h]   The  largest  integer   that  can   be  stored  on  this
implementation is 32759
 [h]
 [i] ? $read
 [i] $REA? 1 1 1 1 0 1
 [i] $REA? 1 1 1 2 0 2
 [i] $REA? 1 2 1 1 0 17
 [i] $REA? 1 2 1 2 0 5
 [i] $REA? 1 2 4 4 2 0
 [i] $REA? 1 3 1 1 0 1
 [i] $REA? 1 3 1 3 0 1
 [i] $REA? 2 2 1 1 1 10
 [i] $REA? 2 2 1 2 1 4
 [i] $REA? 2 2 1 3 0 2
 [i] $REA? 2 2 1 4 0 1
 [i] $REA? 2 2 2 1 0 11
 [i] $REA? 2 2 2 3 0 1
 [i] $REA? 2 2 2 4 1 1
 [i] $REA? 2 3 1 1 0 4
 [i] $REA? 2 3 1 2 2 2
 [i] $REA? 2 3 1 3 3 0
 [i] $REA? 2 3 2 1 0 3
 [i] $REA? 2 3 2 2 2 3
 [i] $REA? 2 3 2 3 1 4
 [i] $REA? 2 3 2 4 3 1
 [i] $REA? 2 3 3 3 0 1
 [i] $REA? 2 4 1 1 0 1
 [i] $REA? 2 5 2 3 1 0
 [i] $REA? 2 5 3 3 0 1
 [i] $REA? 2 5 3 4 1 0
 [i] $REA? 3 2 2 3 0 1
 [i] $REA? 3 3 1 1 1 1
 [i] $REA? 3 3 1 2 0 1
 [i] $REA? 3 3 2 2 5 3
 [i] $REA? 3 3 2 3 18 3
 [i] $REA? 3 3 2 4 2 3
 [i] $REA? 3 3 3 1 0 1
 [i] $REA? 3 3 3 2 1 0
 [i] $REA? 3 3 3 3 4 4
 [i] $REA? 3 3 3 4 4 0
 [i] $REA? 3 3 4 1 1 1
 [i] $REA? 3 3 4 2 1 0
 [i] $REA? 3 3 4 3 1 0
 [i] $REA? 3 4 1 3 0 1
 [i] $REA? 3 4 1 4 0 1
 [i] $REA? 3 4 3 2 1 0
 [i] $REA? 3 4 3 3 1 0
 [i] $REA? 3 4 4 3 2 0
 [i] $REA? 3 5 1 3 0 2
```

```
[i] $REA? 3 5 1 4 0 2
[i] $REA? 3 5 2 3 0 1
[i] $REA? 3 5 3 3 2 0
[i] $REA? 3 5 3 4 2 0
[i] $REA? 3 5 4 2 1 0
[i] $REA? 3 5 4 3 0 1
[i] $REA? 3 5 4 4 4 0$
[i] ? $calc x=aliv+not$
[i] ? $fac clas 3 shap 5 folh 4 rock 4$
[i] ? $yvar aliv$
[i] ? $error b x$
[i] ? $link g$
[i] ? $display m$
[o] Current model:
[o]
[o]   number of units is  52
[o]
[o]   y-variate  ALIV
[o]   weight     *
[o]   offset     *
[o]
[o]   probability distribution is BINOMIAL
[o]     with binomial denominator X
[o]              link function is LOGIT
[o]            scale parameter is 1.000
[o]
[o]   terms =  1
[o]
[i] ? $fit $
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[i] ? $fit :+clas$
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[o] scaled deviance =  98.71 (change =  -45.53) at cycle  3
[o]              d.f. =  49    (change =   -2    )
[o]
[i] ? $look %x2 %df$
[o]    100.4   49.00
[i] ? $fit :+shap$
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[o] scaled deviance =  97.80 (change =  -46.45) at cycle  6
[o]              d.f. =  47    (change =   -4    )
[o]
[i] ? $look %x2 %df$
[o]    90.39   47.00
[i] ? $fit :+folh$
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[o] scaled deviance =  95.54 (change =  -48.71) at cycle  4
[o]              d.f. =  48    (change =   -3    )
[o]
[i] ? $look %x2 %df$
[o]    92.09   48.00
[i] ? $fit :+rock$
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[o] scaled deviance =  92.81 (change =  -51.43) at cycle  4
[o]              d.f. =  48    (change =   -3    )
[o]
[i] ? $look %x2 %df$
[o]    82.02   48.00
[i] ? $fit :+clas + shap + folh + rock$
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[o] scaled deviance = 59.388 (change =  -84.86) at cycle  7
[o]              d.f. = 39     (change =  -12    )
[o]
[i] ? $look %x2 %df$
[o]    55.41   39.00
[i] ? $fit :+clas +shap + folh$
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[o] scaled deviance =  73.74 (change =  -70.51) at cycle  6
[o]              d.f. =  42    (change =   -9    )
[o]
[i] ? $look %x2 %df$
[o]    71.41   42.00
[i] ? $fit :clas + shap + rock$
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[o] scaled deviance = 72.137 at cycle  6
[o]              d.f. = 42
[o]
[i] ? $fit :+clas + shap + rock$
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[o] scaled deviance = 72.137 (change =  -72.11) at cycle  6
[o]              d.f. = 42     (change =   -9    )
[o]
[i] ? $look %x2 %df$
[o]    61.93   42.00
[i] ? $fit :+clas + folh + rock$
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[o] scaled deviance = 64.279 (change =  -79.97) at cycle  5
[o]              d.f. = 43     (change =   -8    )
[o]
[i] ? $look %x2 %df$
[o]    68.52   43.00
[i] ? $fit :+shap + folh + rock$
[o] scaled deviance = 144.25 at cycle  4
[o]              d.f. =  51
[o]
[o] scaled deviance = 61.368 (change =  -82.88) at cycle  6

[o]              d.f. = 41      (change =  -10    )
[o]
[i] ? $look %x2 %df$
[o]    59.04   41.00
[i] ? $stop$
```

Appendix 3 Transition probability matrix for the Clanwilliam cedar

size class	1	2	3	4	5	6	7	8	9	10	11
1	0	0	0	0	0	2.5	34	110	510	1200	2800
2	0.00259	0	0	0	0	0	0	0	0	0	0
3	0	0.1787	0	0	0	0	0	0	0	0	0
4	0	0.0156	0.1615	0	0	0	0	0	0	0	0
5	0	0	0.0249	0.1649	0.7504	0	0	0	0	0	0
6	0	0	0.0195	0.0478	0.0601	0.5063	0	0	0	0	0
7	0	0	0	0.0345	0.0435	0.3685	0.8327	0	0	0	0
8	0	0	0	0	0	0	0.0162	0.9325	0	0	0
9	0	0	0	0	0	0	0.0035	0.0366	0.9327	0	0
10	0	0	0	0	0	0	0	0	0.0441	0.9491	0
11	0	0	0	0	0	0	0	0	0	0.0252	0.997

Appendix 4 Calculations for the derivation of the elasticity matrix from the transition probability matrix for the Clanwilliam cedar.

1 Define the transition probability matrix for the cedar (after Manders 1987)
and multiply by the population vector until the population growth rate (lambda) stabilizes.

	1	2	3	4	5	6	7	8	9	10	11	Years 0	1	2	3		143	144	145	146
1	0	0	0	0	0	25	34	110	510	1200	2800	0	0	0	28.874625	....	102001.88	104072.39	106184.94	108340.39
2	0.002588	0.743	0	0	0	0	0	0	0	0	0	1000	743	552.049	410.17241	....	951.97511	971.29838	991.01405	1011.1301
3	0	0.1787	0.684	0	0	0	0	0	0	0	0	0	178.7	255.0049	273.07451	....	505.85581	516.12333	526.59837	537.28818
4	0	0.0156	0.1615	0.6869	0	0	0	0	0	0	0	0	15.6	51.16849	84.941518	....	289.58475	295.46229	301.45922	307.57795
5	0	0	0.0249	0.1649	0.7504	0	0	0	0	0	0	0	0	7.02207	20.056338	....	223.59933	228.13727	232.76741	237.49161
6	0	0	0.0195	0.0478	0.0801	0.5063	0	0	0	0	0	0	0	4.23033	9.9821963	....	72.28853	73.733203	75.229873	76.756543
7	0	0	0	0.0345	0.0435	0.3885	0.8327	0	0	0	0	0	0	0.5382	4.0777397	....	247.06498	252.07847	257.19385	262.41318
8	0	0	0	0	0	0	0.0162	0.9325	0	0	0	0	0	0	0.0087188	....	45.588989	46.514185	47.458149	48.421284
9	0	0	0	0	0	0	0.0036	0.0366	0.9327	0	0	0	0	0	0.0018837	....	28.91287	29.500319	30.099841	30.711082
10	0	0	0	0	0	0	0	0	0.0441	0.9491	0	0	0	0	0	....	17.903731	18.267488	18.638637	19.017325
11	0	0	0	0	0	0	0	0	0	0.0252	0.997	0	0	0	0	....	19.373817	19.76887	20.16791	20.5771
												1000	937.3	870.01099	831.18993	....	104404.01	106523.27	108685.57	110891.77
													0.9373	0.9282097	0.9553787	....	1.0202986	1.0202987	1.0202988	1.0202989

2 Transpose the transition probability matrix (ie make rows into columns and vice-versa)
and multiply by the population vector until the population growth rate (lambda) stabilizes.

0	0.002588	0	0	0	0	0	0	0	0	0	52632	0.080228	0.0784938	0.0734107	....	13591.746	13867.64	14149.136	14436.347
0	0.743	0.1787	0.0156	0	0	0	0	0	0	0	31	30.3299	28.365803	1542.7702	....	5368438.9	5467208.5	5578186.6	5691418.1
0	0	0.684	0.1615	0.0249	0.0195	0	0	0	0	0	39	30.8439	2586.3367	29000.936	....	7342871.5	7491925.6	7644006	7799173.9
0	0	0	0.6869	0.1649	0.0478	0.0345	0	0	0	0	21	20.4412	67917.698	153186.67	....	11135729	11361771	11592408	11827727
0	0	0	0	0.7504	0.0801	0.0435	0	0	0	0	21	18.9757	85805.672	180842.19	....	9789197.6	9987912.5	10190862	10397527
25	0	0	0	0	0.5063	0.3885	0	0	0	0	13	131357.22	724697.04	984040.89	....	21909297	22354045	22807823	23270812
34	0	0	0	0	0	0.8327	0.0162	0.0036	0	0	56	1788134.8	1674699	1594692.2	....	30467813	31086297	31717337	32361187
110	0	0	0	0	0	0	0.9325	0.0366	0	0	7	5778527.1	6369048.3	6955468.5	....	219409438	223862376	228406727	233043325
510	0	0	0	0	0	0	0	0.9327	0.0441	0	17	26791336	27768314	28701507	....	485469495	495344828	505400206	515659690
1200	0	0	0	0	0	0	0	0	0.9491	0.0252	11	63039411	63536510	63998140	....	807187892	823573436	840291578	857349072
2800	0	0	0	0	0	0	0	0	0	0.997	10	147089810	146649586	146208840	....	1.633E 09	1.667E 09	1.7E 09	1.735E 09
											52758	244615477	246877973	248807259	....	3.231E 09	3.297E 09	3.364E 09	3.432E 09
												4636.6571	1.0092492	1.0078147		1.0202995	1.0202995	1.0202995	1.0202995

lambda is 1.020299

3. Calculate the dominant left and right eigenvectors <v,w>

w	v										
0.9769924	4.206E-06	0.001658	0.002272	0.003446	0.003029	0.00676	0.0009428	0.067897	0.150237	0.249766	0.505459
0.0091181											
0.0048451											
0.0027736											
0.0021416											
0.0006922											
0.0023663											
0.0004366											
0.000277											
0.0001715											
0.0001855											

4. Multiply v * w to get the scaler product
(This must be done in the right order ie. matrix multiplication of vector v X vector w)
this is scaler product is <v,w>
0.0002611

5. Multiply w * v and transpose the resultant matrix
(this matrix gives vij which gets used in the elasticity matrix equation)

4.109E-06	3.836E-08	2.038E-08	1.167E-08	9.008E-09	2.911E-09	9.953E-09	1.836E-09	1.165E-09	7.215E-10	7.804E-10
0.0016199	1.512E-05	8.033E-06	4.599E-06	3.551E-06	1.148E-06	3.923E-06	7.239E-07	4.592E-07	2.844E-07	3.076E-07
0.0022197	2.072E-05	1.101E-05	6.302E-06	4.866E-06	1.573E-06	5.376E-06	9.92E-07	6.293E-07	3.898E-07	4.215E-07
0.0033667	3.142E-05	1.67E-05	9.558E-06	7.38E-06	2.385E-06	8.154E-06	1.505E-06	9.544E-07	5.911E-07	6.394E-07
0.0029593	2.762E-05	1.468E-05	8.401E-06	6.487E-06	2.097E-06	7.167E-06	1.322E-06	8.389E-07	5.196E-07	5.62E-07
0.006624	6.182E-05	3.285E-05	1.881E-05	1.452E-05	4.693E-06	1.604E-05	2.96E-06	1.878E-06	1.163E-06	1.258E-06
0.0009211	8.597E-06	4.568E-06	2.615E-06	2.019E-06	6.526E-07	2.231E-06	4.116E-07	2.611E-07	1.617E-07	1.749E-07
0.0663349	0.0006191	0.000329	0.0001883	0.0001454	4.7E-05	0.0001607	2.964E-05	1.88E-05	1.165E-05	1.26E-05
0.1467804	0.0013699	0.0007279	0.0004167	0.0003217	0.000104	0.0003555	6.559E-05	4.161E-05	2.577E-05	2.787E-05
0.244041	0.0022776	0.0012103	0.0006928	0.0005349	0.0001729	0.0005911	0.0001091	6.918E-05	4.285E-05	4.635E-05
0.4938296	0.0046088	0.002449	0.001402	0.0010825	0.0003499	0.0011961	0.0002207	0.00014	8.671E-05	9.378E-05

6. then elasticity matrix is (aij/lambda)*(vi*wj/<v,w>)
(ie the ijth element of Manders matrix/population growth rate)*(the ijth element of the above matrix/ scaler product)

	1	2	3	4	5	6	7	8	9	10	11
1	0	0	0	0	0	2.733E-05	0.0012707	0.0007586	0.002231	0.0032514	0.0082054
2	0.0157424	0.0421805	0	0	0	0	0	0	0	0	0
3	0	0.0139018	0.0282749	0	0	0	0	0	0	0	0
4	0	0.0018407	0.0101257	0.0246542	0	0	0	0	0	0	0
5	0	0	0.0013723	0.0052024	0.0182794	0	0	0	0	0	0
6	0	0	0.0024066	0.0033756	0.003277	0.0069223	0	0	0	0	0
7	0	0	0	0.0003388	0.0003296	0.000903	0.008976	0	0	0	0
8	0	0	0	0	0	0	0.0097738	0.1036052	0	0	0
9	0	0	0	0	0	0	0.0046724	0.0090152	0.145737	0	0
10	0	0	0	0	0	0	0	0	0.0114567	0.1527202	0
11	0	0	0	0	0	0	0	0	0	0.0082054	0.3511142

Appendix 5 **True Basic program and flow diagram.**

Leslie matrix cedar model

This is a program to model population development of the Clanwilliam cedar under various fire regimes. The input variables are the population transition matrix, the starting population vector, the fire survival vector, the the interval between fires and the number of fires.

```
dim l(11, 11) ... transition matrix
dim x(11)     ... population vector
dim p(11)     ... fire survival

let brnmx=20 ... defines number of fire cycles
let intmx=15 ... defines length of fire free interval

declare def poptot
mat read l
mat read x
mat read p

let t = 0
let format$ ="######.##"
let fmt$ ="########>"
let y$="####>  "
clear

print using fmt$:"year","6","7","8","9","10","11","total"
print

for n = 0 to brnmx ... number of fire cycles
print "fire cycle ",n
for t = 1 to intmx ... t is number of fire free years
mat x = l*x
print using format$: t, x(6), x(7), x(8), x(9), x(10), x(11), poptot(X)
next t
print
let q=12*n+t
for i=6 to 11
 let sum=sum+x(i)
next i
let sum=0
for k = 1 to size( x )
let x(k) = x(k) * p(k)
next k
next n

Data 0, 0, 0, 0, 0, 2.5, 34, 110, 510, 1200, 2800, .002588, 0.7430, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0.1787, 0.6840, 0, 0, 0, 0, 0, 0, 0, 0, 0.0156, 0.1615, 0.6869, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0.0249, 0.1649, 0.7504, 0, 0, 0, 0, 0, 0, 0, 0.0195, 0.0478, 0.0601, 0.5063, 0, 0,
0, 0, 0, 0, 0, 0, 0.0345, 0.0435, 0.3685, 0.8327, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.0162,
```

0.9325, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.0035, 0.0366, 0.9327, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.0441, 0.9491, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.0252, 0.9970 ... **Transition matrix**

Data 52532, 31, 39, 21, 21, 13, 56, 7, 17, 11, 10... **Starting pop**

Data 0.001814, 0.18885, .1566, .1566, .2566, .2336, .22795, .2801, .38325, .6066, .6861 ... **Mortality vector**
end

```
Def poptot( x())
 !sums the components of any vector x
for l = 6 to size( X)
let sum = sum + x(l)
next l

Let poptot = sum
end def
```

Flow diagram of true basic cedar model;

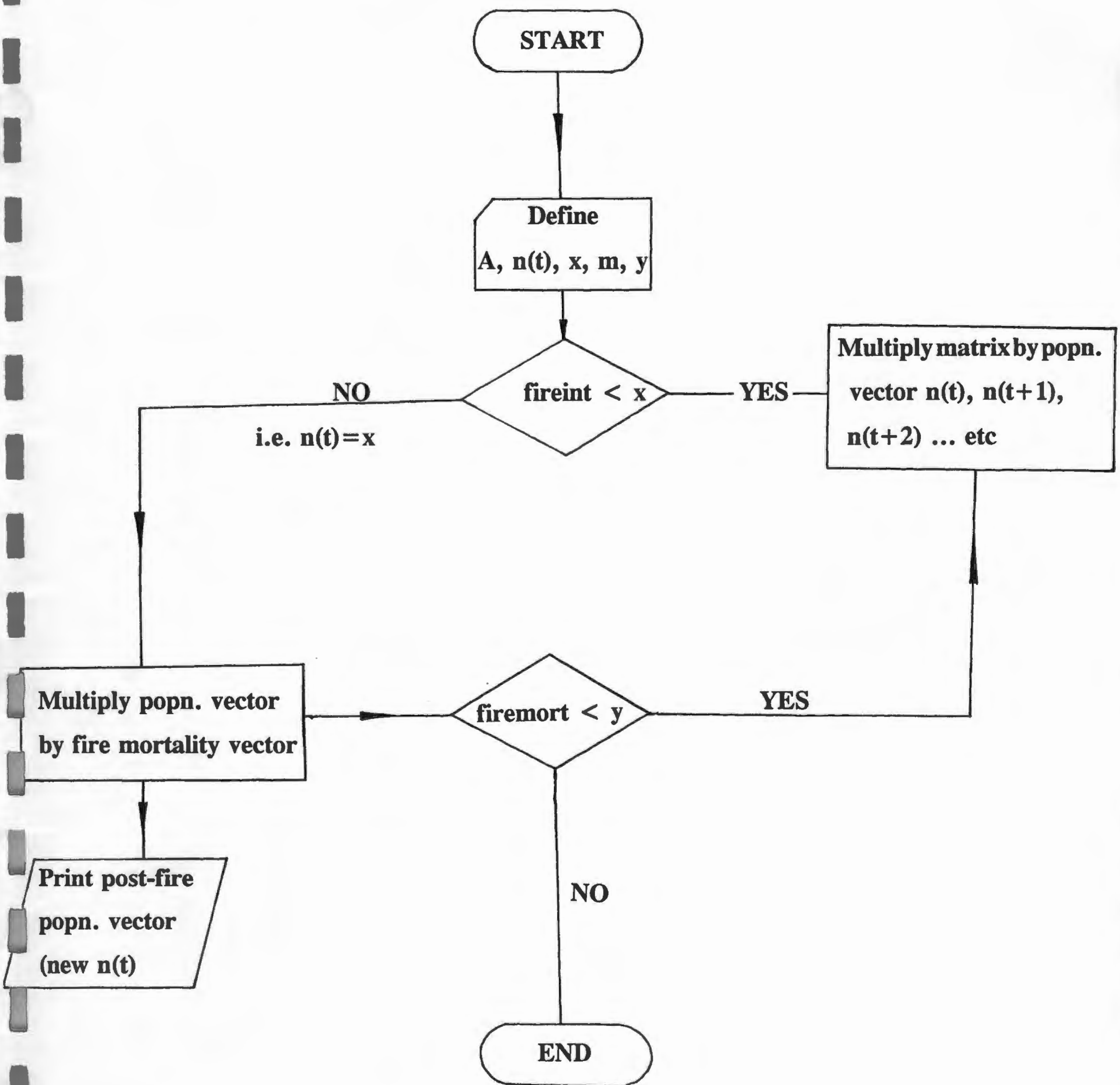
A... transition matrix

n(t)... starting population

x... interval between fires, fireint

m... mortality in fire

y... number of fires, firenum



APPENDIX 6. Starting population and survival data used in model.

Table A. Starting populations.

class	Manders site A	Die Bos	Cedar Reserve
1	52532	59499	49663
2	31	3	34
3	39	3	22
4	21	5	9
5	21	6	11
6	13	11	31
7	56	13	39
8	7	7	24
9	17	6	22
10	11	11	10
11	10	15	8

Table B. Proportion of trees surviving in each size class in prescribed burns, at Forestsum and in wildfires.

CLASS	PRESCRIBED BURNS (Sites A and B)		DIE BOS WILDFIRE (Site C)		SNEEUBERG WILDFIR (Sites D and E)	
	PROPN. SURVIVAL	+ E	PROPN. SURVIVAL	+ E	PROPN. SURVIVAL	+ E
2	0.0645	0.2925	0	0.288	0	0.0852
3	0	0.228	0	0.288	0	0.0852
4	0	0.228	0	0.288	0	0.0852
5	0.2	0.428	0	0.288	0	0.0852
6	0.154	0.382	0.05	0.338	0	0.0852
7	0.111	0.339	0	0.288	0.037	0.1169
8	0.222	0.45	0	0.288	0.0435	0.1102
9	0.43	0.658	0.18	0.468	0	0.1085
10	1	1	0.3	0.588	0.16	0.2132
11	1	1	0.246	0.534	0.2333	0.3722

Table C. Survival figures calculated for a worst case scenario prescribed burn (intermediate) and 8 year rotation prescribed burns.

CLASS	INTERMEDIATE	20% BELOW PRESCRIBE
2	0.1889	0.234
3	0.1566	0.1824
4	0.1566	0.1824
5	0.2566	0.3424
6	0.2336	0.3056
7	0.2279	0.2712
8	0.2801	0.36
9	0.3832	0.5264
10	0.6066	0.8
11	0.6861	0.8