Analysis of the effective spatial scale of neighbourhoods with respect to fire regimes in topographically complex landscapes

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Abstract An understanding of landscape-level variation in long-term fire regimes is fundamental for developing and testing models of vegetation dynamics. Theoretical approaches which synthesise landscape patterns from the well-understood processes that affect fire occurrence and behaviour are useful for investigating the nature of this type of variation. FIRESCAPE is a new process-based simulation model for generating long-term fire regimes in topographically complex landscapes. It simulates spatial variation in fire regimes by combining information on landscape complexity with stochastic weather and ignition generators and algorithms of fire spread. Landscape complexity arises from non-uniform terrain which results in spatial variation in elevation, slope, radiation budgets and soil moisture dynamics, all important determinants of fire occurrence and spread. While there are many applications of the FIRESCAPE model, one that is of particular interest is to investigate the spatial scale of ignition neighbourhoods which may affect the fire regime of a site. In FIRESCAPE, there is no preset neighbourhood size. Rather, the neighbourhood is developed as a function of the simulation process. This paper presents a description of the FIRESCAPE model and describes an analysis of the spatial scale of ignition neighbourhoods and how these are affected by the nature of the landscape within the particular neighbourhood of a site. There appears to be no effect of large-scale topographic features on the spatial extent of the ignition neighbourhoods of sites, however, this results from the opposite effects of slope and the spatial pattern of ignition probability, both of which have significant effects. This research, which characterises the spatial scale of the ignition neighbourhoods of individual sites, is an initial step in developing a theory about the role of landscape complexity, particularly topographic complexity, in determining the nature of fire regimes at particular points in space.

1. INTRODUCTION

The spatial variation of plant communities in topographically complex landscapes arises from the expression of environmental gradients [Austin & Smith, 1989], as well as from the effects of competition, herbivory, disease, and aspects of meta-population dynamics. Disturbances, like fire, are another important consideration [Fox & Fox, 1986; Cary & Morrison, 1995]. The nature of the repeated fires that affect a particular site is known as its fire regime. A fire regime has the characteristics of fire frequency (often represented as the average time between successive fires), fire intensity and season of fire occurrence [Gill, 1975]. An understanding of the nature and causes of spatial variation in fire regimes is, therefore, fundamental to vegetation ecology and represents a growing area of research.

Fire histories have been reconstructed using a number of empirical and statistical methods. Empirical approaches include written and oral histories, fire mapping and pyrodendrochronological studies [Banks, 1982], although these approaches are generally unsuitable for investigating fire regimes at the landscape level because of reasons to do with the length and accuracy of the records and the limitations associated with pyrodendrochronolical studies including tree mortality, missed fire events, and the considerable effort required. Recently, there have been considerable advances made in the application of statistical models for analysing spatial and temporal variation in fire frequency [Van Wagner, 1978] although these models can only be used in conjunction with empirical data.

A number of simulation approaches have been used to construct spatial variation in fire regimes in spatially complex landscapes. These include the approaches used in FIRE-BGC [Keane *et al.*, 1996] a process-based theoretical model of forest dynamics in topographically complex landscapes and the landscape implementation of EMBYR [Gardner *et al.*, 1996]. Both produce theoretical fire regimes that can be used by ecologists, however, they tend to ignore a considerable amount of the well known processes that affect fire occurrence and behaviour. Also, they are generally based on the fire spread algorithms developed by Rothermel [1972] which are not widely used, and hence not well understood, in Australia.

While the primary aim of these process-based simulation approaches may be to characterise the spatial variation in fire regimes for ecological studies, they can also be used to explain the causes of such variation. This paper presents a description of FIRESCAPE, a new fire regime simulator that has sought to address some of the deficiencies in the existing models. The primary function of FIRESCAPE is to produce the inherent landscape patterns in fire regime from the synthesis of well-understood, lower-level processes related to fire occurrence and spread. However, another application of the model is the analysis of the spatial extent of ignition neighbourhoods for individual sites This application represents a first step toward understanding the role of neighbouring landscapes on fire regime characteristics.

2. DESCRIPTION OF THE FIRESCAPE MODEL

FIRESCAPE is a landscape-level fire regime simulation model. It was developed and implemented for the ACT and its surrounding region, and is currently being incorporated into a model that simulates the dynamics of habitat for population viability analysis. The ACT implementation of the model is on a grid of 100 m by 100 m pixels which represent the simulation landscape (total size is around 900,000 ha.). The program for running the model is written in C programming language. The primary input data is a digital elevation model from which a number of important factors that affect fire occurrence and behaviour are derived. FIRESCAPE simulates fire regimes by igniting and spreading individual fires which, through time, results in a landscape-level fire regime.

In the model, daily weather data is generated by a modified version of the Richardson-type stochastic climate generator [Cary & Gallant, 1997] which allows modellers to generate synthetic sequences of weather which are based on the underlying stochastic structure of the meteorological process [Richardson, 1981]. The original model was modified so that it included the variables required for modelling fire danger, an important determinant of fire spread, and to model rainfall amounts using the truncated power normal model [Hutchinson, 1995]. The spatial location of ignition sites are generated by an empirical model of lightning strike location which was developed from data used to construct a similar model by McRae [1992]. In the revised ignition model, the probability of lightning ignition is positively associated with the macro-scale elevation at the broad spatial scale, primarily reflecting the orographic effect of mountain ranges on storm occurrence, and also positively associated with the magnitude of the meso-scale elevation residual at finer spatial scales. These findings, which conflict with the findings of McRae [1992], are more consistent with current understanding of atmospheric electricity and lightning occurrence, and reflect the patterns found in similar studies in Yosemite and Sequoia National Parks, California, USA [Vankat, 1983].

Once ignited, the rate of firespread to neighbours is based on the elliptical fire spread model [Van Wagner, 1969]. This model, along with a number of others including the ovoid fire shape model [Peet, 1967], was found to provide adequate fits to the fire spread contours of 20 low intensity experimental fires burning under uniform fuel and meteorological conditions [Green *et al.*, 1983]. In FIRESCAPE, the spread of fire is modelled on the same system of grid cells as the other data required, compared with the original approach where the position of the fire line was not constrained to a fixed grid. In other words, the fireline propagates by moving from one fixed point to other another fixed point after the appropriate amount of time has elapsed. This has a number of important implications for calculating fireline rates of spread.

Head fire rate of spread is determined for each individual cell using the equation form of McArthur's Forest fire-danger meters [McArthur, 1967]. Hourly meteorological data, fuel load data and drought factor are calculated for individual cells as required. Drought factor is calculated by combining information on the short-term rainfall patterns with longer-term rainfall through the Soil Dryness Index (SDI) [Mount, 1972]. Changes to soil dryness are dependent on the effect of the topography on temperature, rainfall and solar radiation budgets. In the absence of suitable Australian algorithms for modelling the rate of spread of the backfires and length to breadth ratios of fires, the approaches adopted in the Canadian Forest Fire Behaviour Prediction System [Forestry Canada, 1987] were used. Fuel load dynamics are modelled using the empirical approach that was first developed by Olson [1963]. This equation, or modifications of it, has been found to adequately describe the pattern of litter accumulation in a number of Australian systems, including sub-alpine eucalypt and open eucalypt forest. The parameters of the model vary with elevation, as determined from 234 litter quadrats. The fireline intensity (I) ($kW.m^{-1}$) [Byram, 1959] is calculated for the spread of fire from one pixel to the next for the purpose of determining this component of the fire regime and for determining whether a fire spreads, is extinguished, or is not spread but not extinguished.

Each time a cell is burnt, the intensity and time since the last fire are determined. For each cell, the sums and sums of squares of the inter-fire interval and fireline intensity, as well as the number of fires, are stored so that the average and standard deviations can be calculated at any time. The number of fires in each season allows seasonality to be represented as a proportion of total fires. The output of the model includes maps which represent the spatial variation in the various fire regime components. The fire frequency map for the ACT implementation of FIRESCAPE is presented in Figure 1.

The fire frequency outputs of the ACT implementation of the model were compared with the dendrochronological data compiled for *Eucalyptus pauciflora* (snow gum) stands in the Brindabella Ranges by Banks [1982]. Modelled fire frequencies were similar to those reported from tree-ring analysis suggesting that the model is adequately simulating the natural fire regimes, at least for the sub-alpine land systems. Further testing in that study area is more difficult because of the scarcity of long-term fire history data. Further testing of the model would require its implementation in landscapes where there are

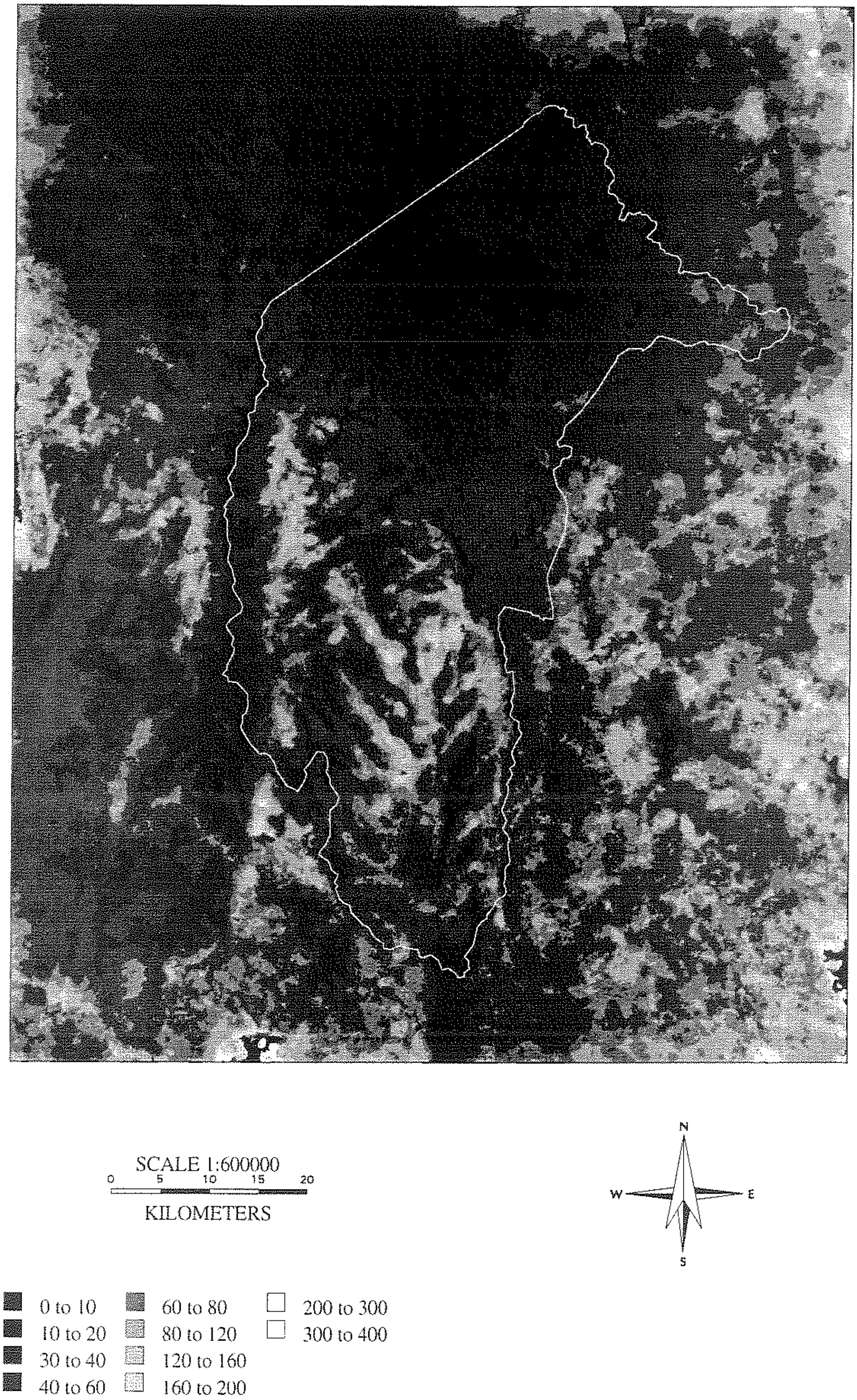

Figure 1:–Average inter-fire interval (years) from a 1000 year FIRESCAPE simulation

comprehensive long-term and spatially extensive dendrochronological data available. The 850 year fire history developed for the Cascade Range, Oregon [Morrison and Swanson, 1990] is an excellent example. Unfortunately, spatial patterns in fire intensity are more difficult to test because of the virtual absence of suitable data.

Also, for a given set of parameters, the outcome of the model is very repeatable so that further investigation does not require a large number of simulation runs. This was tested using three replicate runs of the ACT implementation of the model. The coefficient of variation amongst the replicates for fire frequency and fire intensity for each cell was less than 20% in 84% of cells. This outcome undoubtedly results from the strong influence that landscape structure has on the nature of variation of fire regimes across the study area.

3. ANALYSIS OF IGNITION NEIGHBOURHOOD SIZE USING FIRESCAPE

An ignition neighbourhood can be defined as the area surrounding a site from which all fires which burn the site were originally ignited. The area outside the ignition neighbourhood is irrelevant to the fire regime of the site while the area contained within the ignition neighbourhood will determine the site's long-term fire regime characteristics. This concept can be extended to include the neighbourhood size from which certain percentages (say 25%, 50% and 75%) of ignitions originate. In order to more fully investigate the cause of variation in long-term fire regime, it is important to identify the size of the ignition neighbourhoods of individual sites so that causal factors can be investigated at the appropriate spatial scale.

In FIRESCAPE, there is no preset ignition neighbourhood size. Rather, the spatial scale of the ignition neighbourhood is developed as a function of the simulation process. Therefore, the model can be used to identify the spatial scale of the ignition neighbourhood of individual sites. Further, the effect of individual factors that might affect ignition neighbourhood size can be assessed individually. These factors would include slope and spatial variation in ignition probability, and to a lesser extent, prevailing wind direction and its interaction with slope and ignition locations [Gilbert, 1959], as well as the flammability of the landscape within it [Bergeron and Gagnon, 1987].

Slope is an important factor because fires spread more rapidly in an upslope direction compared with down slope [McArthur, 1967]. Therefore, it is likely that the ignition neighbourhood of a site on top of a major range would be larger than for a site within a valley since fires can, in general, burn further within a given time period to ignite it. The spatial scale of the ignition neighbourhoods of sites on relatively flat plains should be between the two.

The spatial pattern of ignition probability in the landscape is also important because the probability of ignition is positively related to the meso-scale elevation residual. Therefore, for peaks and ranges, it is likely that more ignitions will come from nearby, rather than further afield, compared with the situation for valleys.

The remainder of this paper describes an analysis of the spatial scale of ignition neighbourhoods, defined as the size of the neighbourhoods from which various proportions of ignitions originate, and how this is affected by the position of the site in the landscape which has important implications with respect to slope and spatial patterns of ignition probability.

3.1 Methods

FIRESCAPE simulations were used to identify the ignition neighbourhoods of three different types of sites:- i) sites located near the top of major peaks or ranges (range); sites located near the bottom of major valleys (valley); and sites located on plains (plain). Three replicates of each type of site was used in the analysis. The replicate sites were chosen to represent unambiguous landscape position and therefore are not random, but are representative of typical features within each site classification. The sites were chosen prior to the generation of any information concerning the spatial extent of ignition neighbourhoods.

Three different simulations were performed. Firstly, the extent of the ignition neighbourhoods was determined with the effect of slope and spatial pattern of ignition probability removed from the model. The importance of the pattern of ignition probability was determined by including its effect in a second simulation. Finally, the added effect of slope was determined by also including it, along with the spatial pattern of ignition, in a third simulation which represents the situation under which real ignition neighbourhoods are most likely generated. All simulations were of 1000 years duration.

The ignition points of all fires that burnt a site were recorded for each simulation and the spatial extent of the ignition neighbourhoods was determined by comparing the average distances (and standard error), from the site of interest, that would encompass 25%, 50% and 75% of all the ignition points that influenced it.

3.2 Results

The average spatial extent of the ignition neighbourhoods for each simulation type and for each site classification is shown in Figure 2.

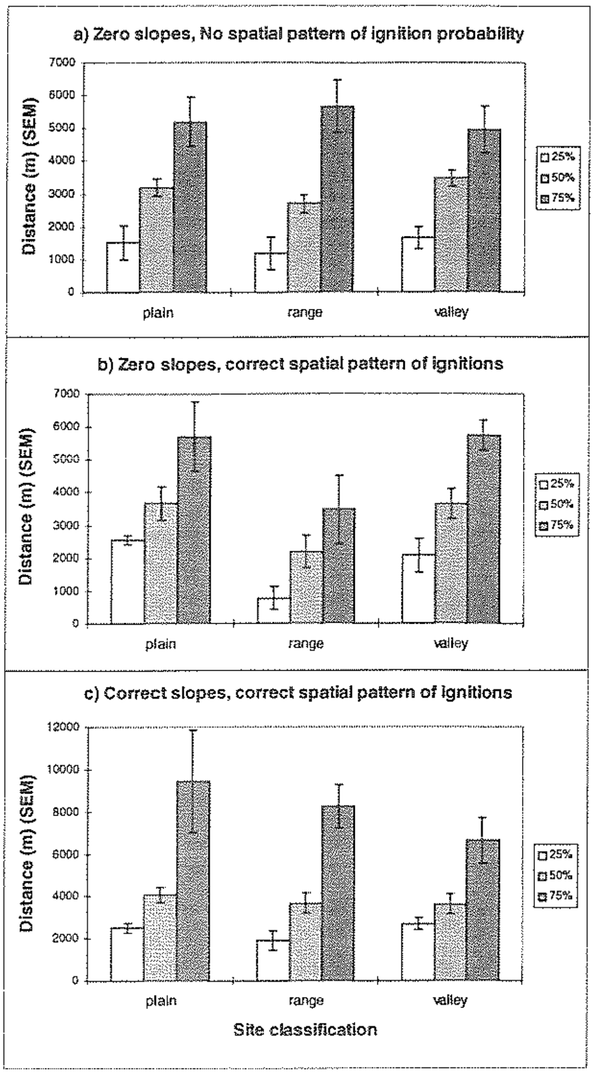

Figure 2:- Average distances (metres) to the 25th, 50th and 75th percentile of ignition points for the 3 replicates in each site classifications. a) Simulation of distance with no effect of slope or spatial pattern in ignition probability. b) Simulation with no effect of slope but with the observed spatial pattern of ignition probability. c) Simulation with observed slope and observed spatial pattern of ignition probability. Site classifications are:- plain (sites located on relatively large, flat areas); range (sites located on top of major peaks or ranges); and valley (sites located near the bottom of major valleys).

With the effect of slope and spatial pattern in ignition probability removed (Figure 2a), there is little apparent difference between the spatial nature of the ignition neighbourhoods for plain, range and valley sites. This result indicates that other factors that may effect the spatial extent of ignition neighbourhoods may have relatively little effect. It also indicates that any differences between the size of ignition neighbourhoods in further simulations may be attributable to the effects of slope and the spatial patterns in ignition probabilities.

The addition of the spatial pattern of ignition probability has a marked effect on the size of ignition neighbourhoods (Figure 2b). Clearly, the increased probability of ignition near peaks and ranges, because of the positive relationship between ignition probability and meso-scale elevation residual, has effectively reduced the size of the ignition neighbourhoods for these sites since more ignitions are coming from a closer proximity, and less from further afield, as expected. The spatial extent of the 25th, 50th and 75th percentile of ignition ranges are considerably less than that for the valley and plains sites which are more equivalent.

Adding the effect of slope to this has the result of increasing the effective size of the ignition neighbourhoods of range sites because of the effect of slope on the rate of spread of fires. Consequently, the spatial extent of the range sites increases to be:- intermediate between plain and valley sites for the 75th percentile; equivalent to the valley and plain sites for the 50th percentile; and below the valley and plain sites for the 25th percentile distances, although the final differences between any of the site classifications is quite small (Figure 2c). One interesting result from the addition of the effect of slope into the model is the overall increase in the 75th percentile distance for the plain sites. This result contributes significantly to the final size of the ignition neighbourhoods.

3.3 Discussion

Analyses of the spatial extent of ignition neighbourhoods is a first step toward understanding the interaction between landscape variation and spatial variation in fire regimes.

There was little appreciable difference between the spatial extent of the 25th, 50th and 75th percentiles of ignition occurrence between the three different types of sites in the final "realistic" simulation, although the 75th percentile distance for the plain sites is slightly larger than for valleys. This result, without the intermediate simulations, may suggest that neither slope nor the spatial pattern in ignition probability effects the spatial extent of ignition neighbourhoods. This is clearly not the case since the effect of slope and ignition probability have significant effects, particularly on range sites. The major finding then is that the two process tend to be compensatory, particularly for the range sites.

The complex processes involved in determining the spatial extents of ignition neighbourhoods in topographically complex landscapes could not be determined from empirical approaches involving fire history maps. Firstly, most empirical approaches only show the extent of the final fire boundary, not the ignition location [although see McRae, 1992].

Secondly, and more importantly, the ignition neighbourhoods determined from these data sets would be equivalent to the third simulation where the effect of one factor is largely compensated by the effect of another. Only by using a process-based model where the effects of particular phenomena can be removed, can the process be fully understood.

Having determined the characteristics of ignition neighbourhoods, the development of theories about landscape-induced variation in fire regimes can be developed further since the extent of the neighbourhoods have been identified as have the important processes determining it. This is a significant step forward.

4. ACKNOWLEDGMENTS

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