Landscape Ecology **15:** 373–381, 2000.

Fire-driven dynamic mosaics in the Great Victoria Desert, Australia

I. Fire geometry

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Received 25 August 1998; Revised 10 May 1999; Accepted 10 July 1999

Key words: fire shape, Great Victoria Desert, habitat mosaics, shape statistics, succession, wild fires

Abstract

The dominant ground cover in the Great Victoria Desert is porcupine grass or spinifex, a fire-prone perennial grass that grows in hummocks or tussocks. Lightning sets hundreds of wildfires annually in inland arid Australia, generating an ever changing spatial-temporal patchwork of habitats that differ in their state of post-fire recovery. The spatial configuration of this patchwork is determined by the size, shape, frequency and inter-spatial relationships of fires, and is likely to play a vital role in the maintenance of the desert biota. Chronosequences of satellite imagery spanning the years 1972–1991 are used to extract and describe the geometry of over 800 fires from fire scars. In the imagery study area, an average of 43 fires occur annually, fire size frequency distributions are roughly log-normal with mild right skew, with average area of 28 km^2, burning between 2 and 5% of the burnable landscape each year. Average fire return interval is estimated to be at least 20 years. These empirical findings are an important prerequisite for developing a more sophisticated understanding of the dynamics of the fire cycle in this ecosystem.

Introduction

Fires have played an important role in the evolution of Australia's flora and fauna, and continue today to maintain habitat heterogeneity and to facilitate and maintain species diversity in both plants and animals (Gill et al. 1981; Pyne 1991). The Great Victoria Desert (GVD) of Western Australia is a vast and largely pristine ecosystem extending over nearly half a million square kilometers (Shephard 1995; Greenslade, 1986). The GVD supports a uniquely rich and diverse lizard fauna (Pianka 1989, 1992, 1996). At least a dozen different factors contribute to this exceedingly high diversity in Australian deserts (Pianka 1989, 1994). One of the most important is frequent natural wildfires, which generate a patchwork of habitats in various states of recovery, each of which favors a different subset of species (Pianka 1992, 1996; Masters 1996). Habitat-specialized species can go locally extinct within a given habitat patch, but still persist in the overall system by periodic re-invasions from adjacent or nearby patches of suitable habitat. Species that persist in this way will likely have dispersal properties that permit them to track available habitat as it revolves through the fire-succession cycle, and life-history characteristics that enable them to utilize habitat patches of a size commonly available. Since patch size and inter-patch distances result directly from the spatial patterning and scale of disturbance, the survival of such diverse species assemblages as regional metapopulations depends not only on periodic disturbance from the fire cycle, but also on the application of this disturbance at a very precise physical scale.

Satellite imagery offers a powerful way to acquire regional level data on frequency and phenomenology of wild fires, and thus system-wide spatial-temporal dynamics of disturbance. This information can be used to develop computer models designed to study the sensitivity of the structure of habitat mosaics to changes in dynamics of the fire cycle. Such knowledge is required at an applied level for design of appropriate land management strategies in the GVD, and also raises interesting questions about the role of relative spatial scale in maintenance of stable metapopulation dynamics. The relatively simple successional process and the unambiguous nature of disturbance in this region makes it an ideal system in which to study the dynamics of the physical architecture that mediates the interaction of landscape and metapopulation ecology (see Wiens, 1997, for a review of this perspective). Furthermore, inland Australia is among the last areas where natural wildfires remain a regular and dominant feature of an extensive semi-pristine natural landscape largely undisturbed by humans. It may well offer the last opportunity to study the regional effects of disturbance on local diversity in pristine terrestrial ecosystems.

Fire cycles

The Great Victoria desert contains a mixture of different landforms, including extensive gently undulating plains, plains with closely spaced sandridges or confused dunes, gibber covered plains, silcrete rises and laterite breakaways, shallow depressions, and chains of dry saltlakes. The majority of the area (about 70% of the total 42 million hectares) consists of sandplains and sandridges covered with spinifex hummock grasses, but shrubs and mulga prevail on harder substrate types and in dry lakebeds.

Burbidge (1943) was among the first to comment on succession following disturbance caused by wild fires in Australia, noting the rapid response of the pyrophyte *Triodia pungens*. In the GVD, plant cover has been estimated to range from 28–41%, and is 96–98% comprised of a monospecific carpet of spinifex grass *Triodia basedowi* which contributes to observed standing crop weights of 317–569 g/m^2 (see Winkworth 1967). *Triodia basedowi* is a fire-prone perennial grass that grows in hummocks or tussocks. Newly-burned areas are usually quite open with extensive bare ground and tiny, well-spaced, clumps of *Triodia*. With time and precipitation, *Triodia* clumps grow, simultaneously increasing combustible material and reducing gaps between tussocks, both of which are likely to increase the probability of fire spread (Gill et al. 1995). Unburned patches are composed of large old tussocks, frequently close together with little open space between them.

Spinifex fires in western and central Australia were studied by Griffin et al. (1983), Griffin and Allan (1984), Allan and Griffin (1986), Griffin et al. (1988), Burrows et al. (1991) and reviewed by Ralph (1984). Griffin et al. (1983) estimated that approximately 60% of wild fires in this region were started by lightning. The majority of grassland fires burn along two 'fronts'. The 'backfire' burns slowly into the wind, whereas the 'headfire' burns faster racing with the wind. Headfires often break up into long tongues of flame which parallel prevailing wind direction at the time of the fire (Burrows et al. 1991). Backfires typically die out before headfires, leaving a single front. A patch of open ground as small as 10 m by 10 m can disrupt a head fire and break it into two (Burrows et al. 1991). Airborne flaming materials ('firebrands') sometimes jump across unburned areas to rekindle new fires several hundred meters downwind (leeward) of a fire, resulting in establishment of multiple fire fronts. With a lot of combustible material, fire fronts burn virtually everything in their path, leaving behind an almost completely burned swath. However, when grass is green or wet and therefore less flammable and/or if tussocks are widely spaced and/or if winds are weak, fires may falter and die out. When there is little or no wind, however, a fire may not 'take' even in a fairly combustible situation. Fires frequently die out at night when lower temperatures cause winds to die down and relative humidity to increase. Spinifex fuels are generally too light to smoulder for long, however denser fuels may leave hot embers from which fires may flare up again if winds revive.

Winkworth (1967) suggested that all spinifex communities are in a state of cyclic development from fire to fire. He estimated that, in the Northern Territory, only about 20% of some 150 000 km^2 of spinifex habitat is in a 'mature' climax state, with the other 80% either in regenerative stages following fires or in a degenerative state owing to drought. Fires vary in intensity but usually most spinifex is burned (except for unburned refuges). Spinifex roots survive and regrowth can be rapid following rain. Spinifex fills in gaps both vegetatively and by setting seed and this rapid vegetative recovery ensures a high level of fire activity. Fire return intervals have been suggested to be as short as 3–10 years (Kimber, 1983). Burned plots converge on their original state quickly; in 7 years, dry weight production of spinifex totaled 82 g/m^2, approximately one quarter of the standing crop of 'mature' stands at a nearby site (Winkworth 1967).

An analysis of over 5000 fires collated over an area of 750 000 km^2 in the southern half of the Northern Territory between 1950 and 1984 revealed that within

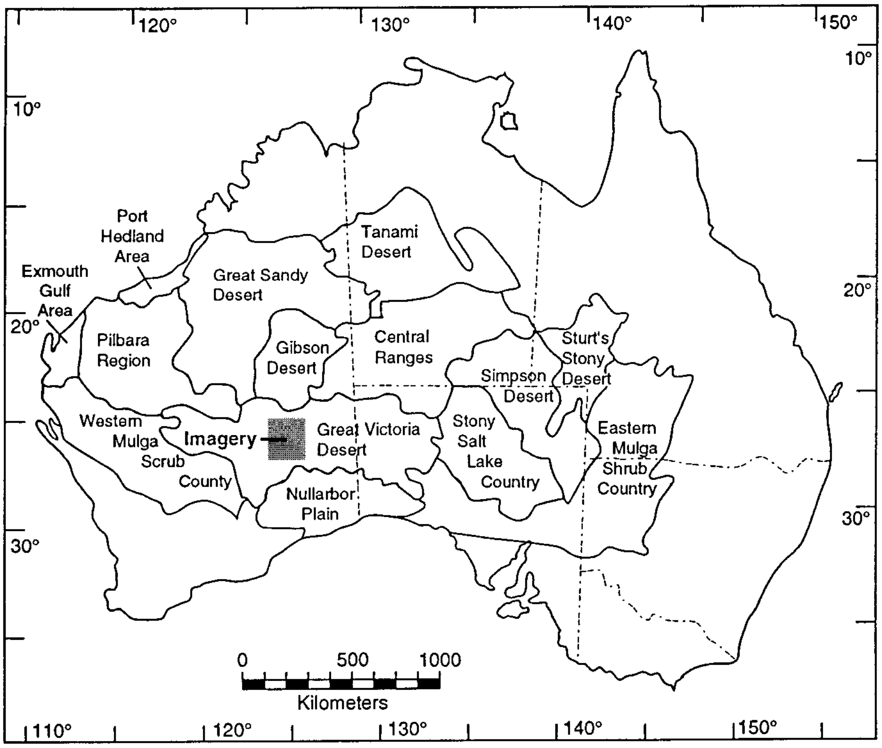

Figure 1. Map showing locations of various regions in the Australian arid zone. The Great Victoria Desert stretches from western South Australia over a thousand kilometers into south central Western Australia. Approximate position of the MSS imagery study area is also shown (Figure modified from Pianka, 1969).

wetter, more productive areas, fires were not only more frequent and more numerous but also patches were more variable in size and tended to be younger on average (Griffin et al. 1988). Following periods of low rainfall, fires were less frequent and smaller.

Fire return intervals appear to be longer in the GVD (see below) due probably to lower precipitation. Time required for a burned stand to reach maturity is a function of precipitation, and can require as long as 20–25 years, sometimes even longer. Fuel load recovery is a function of time and total rainfall. Cumulative millimeters of precipitation has proven to be a useful temporal productivity metric against which to calibrate fires and vulnerability to fire (Griffin et al. 1988). Approximately 63 cm of rain were necessary for a site to accumulate sufficient fuel to reburn in the Northern Territory (Griffin et al. 1988). Rainfall in the GVD is variable, peaking during the summer months, with an average annual precipitation of 23.27, SD = 12.92 (Pianka 1986).

Methods

A dozen Landsat multispectral scanner (MSS) satellite images from each of two adjacent locations (which include Red Sands, Warburton, Lake Throssel, Lake Rason, and Yamarna Homestead) were acquired over the 20 year interval from 1972 to 1991, including all years from 1979–1988 (Figures 1 and 2). No imagery is available between 1973 and 1978. The area chosen for analysis is approximately 185 km E–W by 370 km N–S, and therefore represents about 68 450 km^2. All scenes were acquired during October or November. Resolution of MSS imagery is 80 m × 80 m (one pixel in visual displays). Images were de-striped, corrected for earth curvature, radiometrically corrected, and georeferenced (geometrically registered) to one another by stapling images together at identifiable known control points and rubber sheeting (Barrett and Curtis 1992).

ERDAS-Imagine Geographical Information Systems (1995) were used to make up chronosequence images of various combinations of three different years (such as 79–80–81, 85–86–87, or 72–81–91) us-

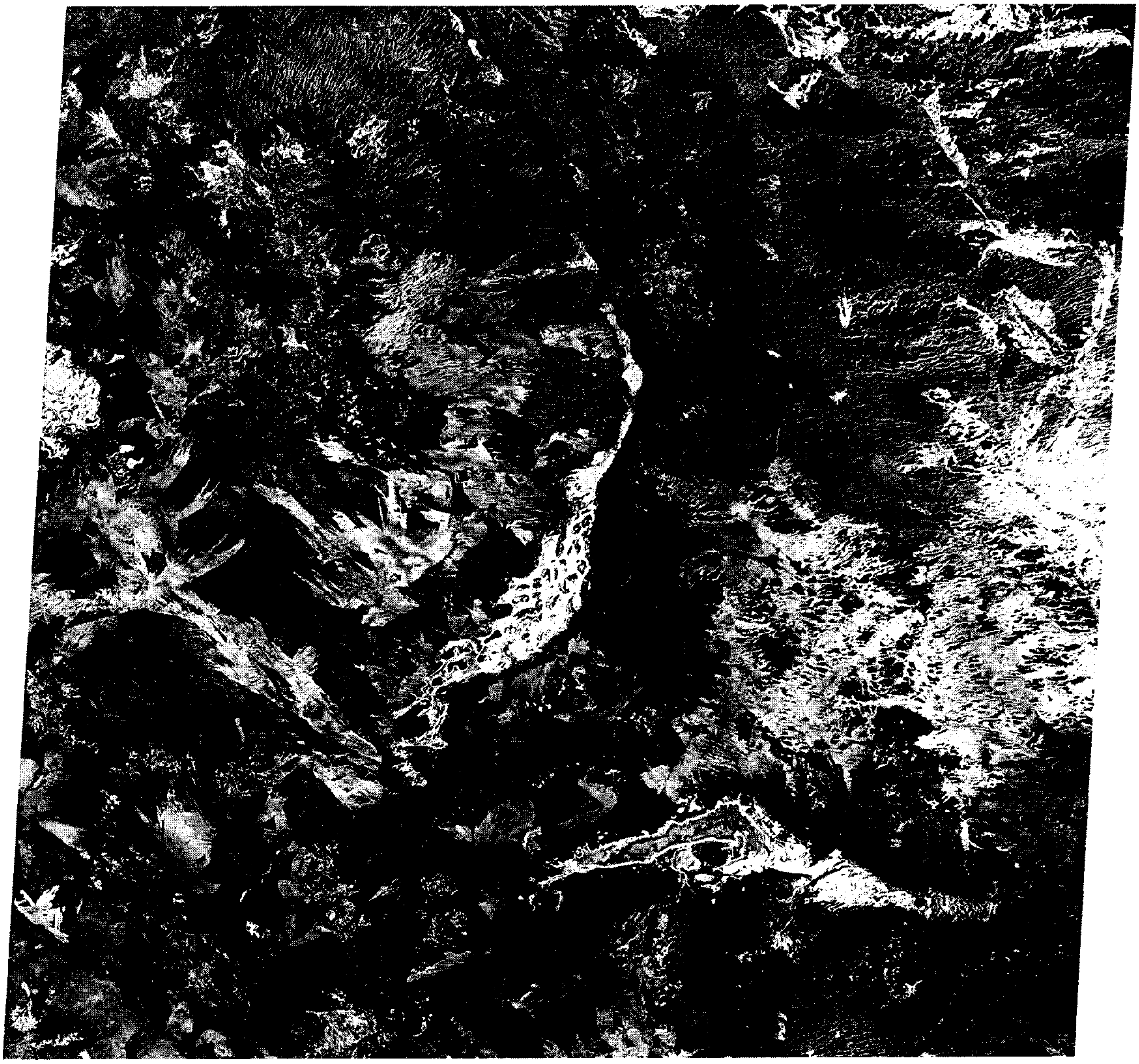

Figure 2. Landsat MSS satellite image showing the habitat mosaic in the southern scene during 1988. Scene is approximately 34225 km^2. Fire scars, most easily visible in the western half of the scene are various shades of light gray depending upon their age – note that many fires are highly laciniated. Two major dry lakebeds (Lake Throssell and Lake Yeo), which act as fire breaks, are also present in the east and south. Sandridges are fine east-west striations. Dark gray and black patches are non-burnable shrub-*Acacia* habitats.

ing the far infrared band 4. In this band 4, sand and ash reflect whereas vegetation absorbs. Single false colored 3-layered composite images were generated with the oldest scene on the bottom (blue), the mid-sequence scene in the center (green), and the latest scene on top (red). Fires represented only in the most recent (top) scene stand out vividly in red, whereas fires present in two years (center and top) are yellow (green plus red). Fire scars present in all three scenes are white (blue + green + red). Some fire scars were extracted by hand digitizing; others were obtained with Imagine, using a pixel growth routine that acquires neighboring pixels within a certain specified spectral Euclidean distance of selected average 'target' pixels. Multiple fires that burned together during the same year could not be distinguished and therefore had to be treated as a single large fire, although one could sometimes see that several fires were probably involved. Groups of pixels resembling fires but less than 4 pixels in area were ignored. Some 817 fire scars were extracted from the data. All fires from the southern scene were examined in greater detail. About half (187) of these 341 fires could be aged to the exact year in which they occurred (i.e, those that burned between 1980 and 1988, over which time interval coverage is annual). However, we could not date fires that burned before 1972 with any degree of precision. Fires that burned between 1972 and 1979 and those that burned between 1988 and 1991 could also not be dated to the nearest year. By examining overlapping fire scars we were able to establish approximately the fraction of the landscape that had burned more than once.

For each fire, we measured: area, (including and excluding internal unburnt areas) total perimeter (including the perimeter of included unburned patches), major and minor axes (the longest axis, and that orthogonal to the longest axis), number of tongues, and a measure of edge simplicity that represents the ratio of a fire's actual area to the area of a circle with the same perimeter as the fire. This edge simplicity index was derived as follows: given that for a circle of radius r, $P = 2\pi r$, then $r = P/2\pi$, and $r^2 = P^2/4\pi^2$. Substituting the last expression for r^2 into $A = \pi r^2$, dividing actual fire area by the result, and simplifying, gives $4\pi A/P^2$, where A and P are the actual area and perimeter of the fire, respectively (see Stoyan and Stoyan 1994). A ratio of one indicates a fire has a circular shape. Fires with lower ratios have more complicated perimeter structures.

The relationship between perimeter and area of fires was modeled by the relationship $P = kA^g$. Constants k and g were estimated from the log-log plot of perimeter versus area.

We developed an algorithm to extract elongated tongues from fires, which were then used to determine tongue compass orientations. This technique used variable length 'worms' wrapped around the outside perimeter of fires and moved around the outer perimeter of the fire until the Euclidean distance between the two tips of the worm diminished sharply, at which point the tongue is cut off from the main body of the fire scar. This procedure enabled acquisition of compass directions for hundreds of tongues, which were compared to wind direction probabilities.

Information on wind direction at 5 m above ground level was acquired from the Australian Meteorological Bureau in Perth. These data were collected at the Yamarna weather station located near the center of the imagery about 8–10 km east of the Red Sands study site, and spanned 19 years (1977 through 1996).

Table 1. Descriptive statistics for five variables ($N = 817$ fires).

Statistic	Mean	SD	Min.	Max.
Area (km^2)	27.85	134.23	0.03	2799
Perimeter (km)	75.68	312.82	0.80	6826
Perimeter/Area	8.19	5.33	1.37	30.00
Major/minor	2.47	1.36	1.03	16.78
Edge simplicity index	0.189	0.12	0.006	0.628

Careful examination of reburned areas allowed us to deduce (1) how often a fire burned adjacent to pixels containing vegetation of known age, (2) how often fire spread to these pixels and (3) how often these pixels formed part of the fire's unburned edge. Probabilities that a pixel of a particular age exposed to fire would 'carry' that fire were thus estimated.

Results

Vital statistics for fires observed in both locations are presented in Table 1.

Frequency distributions of log area, log perimeter, edge simplicity index and the ratio of the lengths of major to minor axes are illustrated in figure 3A-D. Most fires are small (half are less than 2 km^2) and distributions of area and perimeter are right skewed. Edge simplicity indices are also right skewed.

Area and perimeter are tightly correlated ($r = 0.986$, 95% C.I. 0.984 to 0.988). The log-log plot of perimeter on area is approximately linear (Figure 4A) and log k and g were estimated as 2.86 and 0.718, respectively. About half the fires, especially smaller ones, contained no internal unburned patches, while larger fires contained more unburned refuges. On average only 3% of a fire scar's internal area remained unburnt, they were on average 97% 'solid'. Larger fires had more tongues than smaller fires (Figure 4B, $r = 0.684$, 95% C.I. 0.623 to 0.737); and exhibited more complex perimeter geometry (Figure 4C, $r = -0.792$, 95% C.I. -0.829 to -0.749) but were not proportionately more elongated than smaller fires (Figure 4D, $r = 0.077$, 95% C.I. -0.029 to 0.182).

Wind direction probabilities for 19 years (1977–1996) of afternoon winds, are presented in Figure 5A. Winter is June–July–August, spring is September–October–November, summer is December-January-February, autumn is March–April–May. There are no striking seasonal differences in directions of prevailing

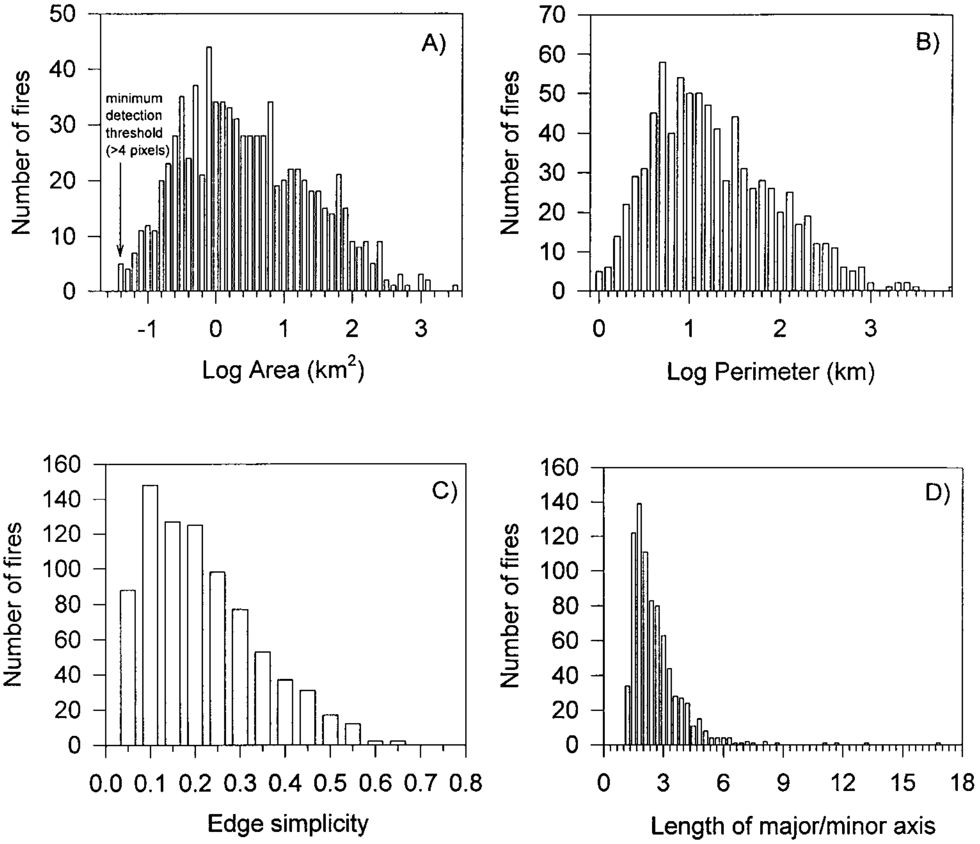

Figure 3. Count density distributions of 817 fires. (A) the logarithm of fire area, (B) logarithm of fire perimeter (including internal edges of unburned patches), (C) the edge simplicity index (see text for details), and (D) the ratio of lengths of major to minor axes of scars.

winds, southeasterly winds prevail in all four seasons with ESE winds being secondary, but during winter and spring, winds are slightly more likely to be from the west and northwest (data on wind strength is discussed in detail in the companion paper – Haydon et al. 1999).

Orientation of 196 identified tongues from 224 fires in the southern scene are shown in Figure 5B. Prevailing directions of winds and tongues correspond fairly well.

An average of 43 fires per year were observed over both scenes, which burned an average of 1197 km^2 annually, this corresponds to 2% of the landscape burning each year (see Figures 6A and B). Fire activity was greatest in an area of ~34 000 km^2 located in the northern half of the southern scene, where an average of just over 20 fires per year was observed. This corresponds to an average of just under 4.0×10^{-6} fire ignition events per pixel per year. In this area 9895 km^2 burned at least once, and 503 km^2 burned twice (this corresponds to a 4.84% reburn in 20 years). Within this area empirically derived probabilities of pixels of any given age carrying a fire (conditional on a fire occurring adjacent to it) were calculated and are presented in Table 2. Note that these probabilities are, by necessity, calculated during conditions conducive to fire spread and would presumably be reduced, perhaps substantially, under conditions less conducive to combustion.

Discussion

Fire sizes in the GVD are approximately log-normally distributed, but possess a clear right skew indicating that mean fire size is greatly influenced by a few very large fires. Mean fire size of the entire sample is 27.85 km^2, but if the largest 7 fires are excluded from the sample, the mean drops to 18.43 km^2. The modal fire size is ~0.8 km^2, and this is over 30 times the minimum detection threshold (0.0256 km^2) so we consider that intermediate sized fires really are a good deal

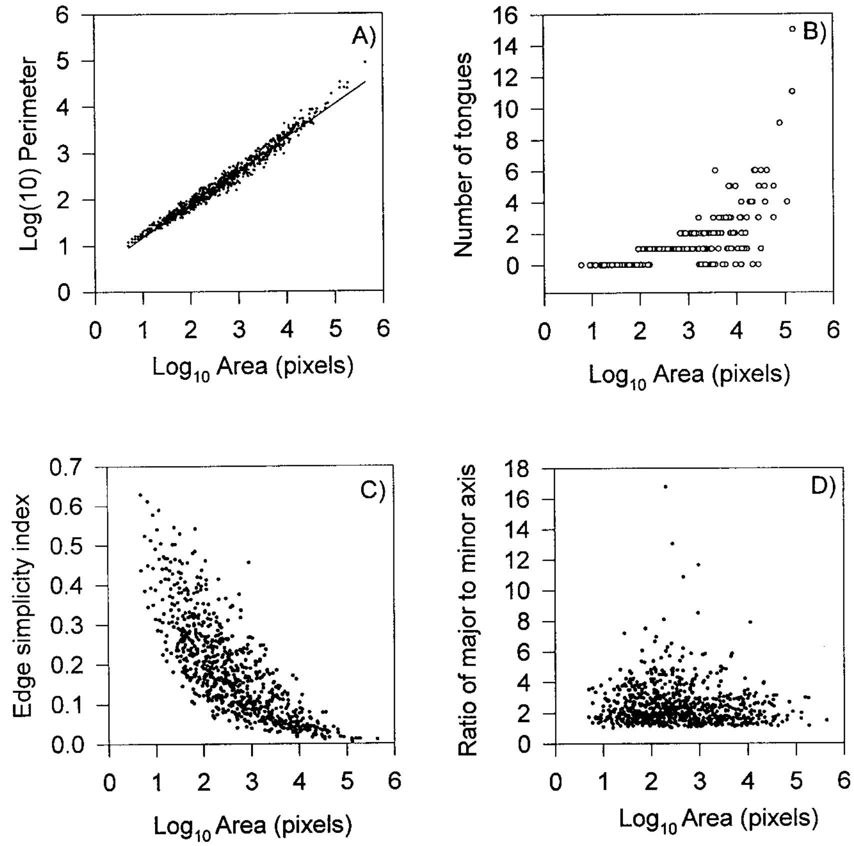

Figure 4. Plots of (A) log perimeter, (B) number of tongues, (C) edge simplicity and (D) elongation against log fire area for 817 fires, except for (B) which used only 341.

Table 2. Estimated probabilities that a pixel of a given age will actually burn given that at least one adjacent pixel burnt.

Age	Probability of carrying a fire
1–5	0.52
6–10	0.77
11–15	0.85
16–20	0.83

more common than smaller fires, and that this mode is not an artifact of our 4-pixel size threshold. However, obvious uncertainty remains regarding the actual frequency of fires beneath this detection threshold.

Comparison of our fire sizes with a subset of those reported by Griffin et al. (1988, Figure 2) suggests that our fires were on average approximately half the size. ‘Binning’ our 817 fires in the same way as Griffin et al. (1988) leads to a unimodal distribution with just over half (414 of 817) the fires less than 2 km^2. Calculation of the Shannon–Wiener index for the distribution of fire sizes calculated this way gives a value of 1.67, about double that reported by Griffin et al. (1988). It is possible that these differences arise from the different methods used in identifying fire scars.

Average ratio of major to minor axes was ~2 and suggests that fires tend towards an oblongate form. The largest fires tend to burn NE–SW (data not shown). Perimeters of larger fires are more complex than smaller fires, consistent with the observations of Eberhart and Woodard (1987) for forest fires in Alberta. Larger fires have more tongues than smaller fires, and these tend to be oriented with prevailing winds suggesting that wind is an important determinant of both fire size and shape.

The exponent relating the scaling of perimeter to area is 0.74, considerably greater than that of regular two dimensional objects (for which it is 0.5), sug-

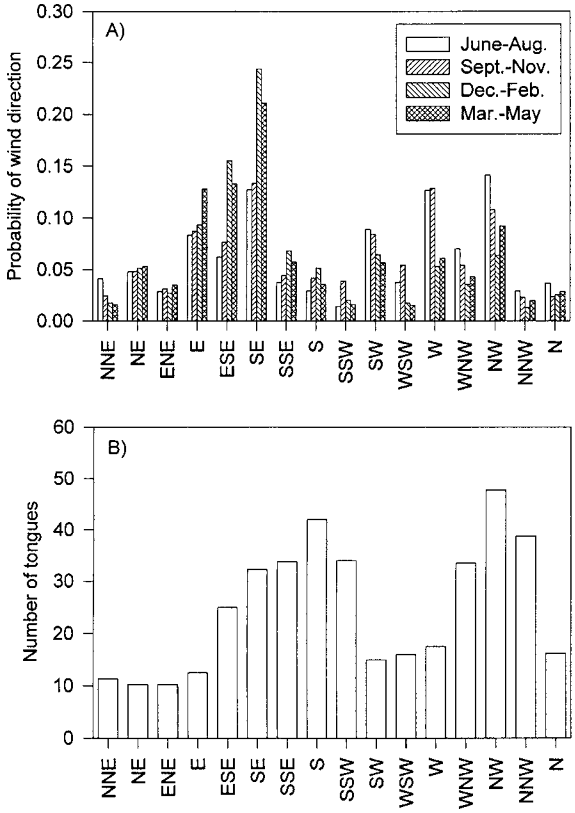

Figure 5. (A) Prevailing wind directions by season. (B) Orientation of tongue directions as found on the fire scars.

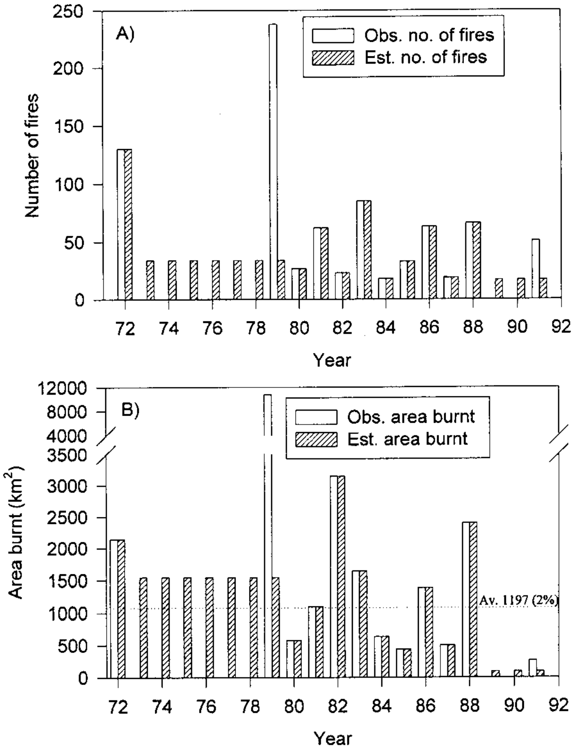

Figure 6. (A) Numbers of fires per year in both the north and south scenes, (combined area 68,450 km^2). (B) The total area burnt each year in both scenes. The dotted line indicates mean annual area burned, which corresponds to 2% of the area studied. Estimated values are simply observed values divided evenly over years which observations accumulated.

gesting that this population of fires is in some sense 'fractal'. This observation is consistent with the observed negative correlation between edge simplicity index (average = 0.189) and fire area. Fractal dimension can be estimated at 1/0.74 = 1.35, a figure somewhat higher than 1.15 reported for 14 forest fires by McAlpine and Wotton (1992) estimated using a more direct methodology.

Our analysis suggests between 2–5% of the landscape burns each year, and that average fire return interval in this system is not less than 20 years. Annual area burned is greatly distorted by extensive and unusual fire activity in 1982. Whether this elevated level of fire activity is a regular quasi-periodic phenomenon, a function of climate change, or simply an aberration is not clear. Longer time series analysis would be required to distinguish between these alternatives. However, results from dynamic models of this system suggest that approximate cycles of long period could easily arise (Haydon et al. 1999).

Analysis of re-burned areas suggests that as expected, older fuel rich habitats are more prone to carry fires than younger habitats that contain a reduced density of combustible biomass.

The proportion of fires in this landscape that start by human practices is unknown, it is known that aboriginals do light some fires in this region. Virtually no domestic stock graze this virtually waterless region, except for a few sheep around the edges of the desert. Only a few tracks penetrate the region, one major east-west route and one north-south one. The only effort to suppress fire are burning bans imposed by the Laverton shire council (typically from October through February).

This description of the basic unit of large scale regional disturbance in this system is an important prerequisite to understanding landscape dynamics determining the large scale ecology of this environment. These baseline data can be used to construct and tune computer simulation models of the physical dynamics of this landscape to ascertain effects of different fire management regimes on the patch structure of the landscape. We develop such a model in the subsequent paper.

Acknowledgements

We particularly wish to thank Professor Melba Crawford and many of the students in her group for much help and guidance with respect to the image analysis. This research has been financed by grants from the National Geographic Society, the John Simon Guggenheim Memorial Foundation, a senior Fulbright Research Scholarship, the Australian-American Educational Foundation, the University Research Institute of the Graduate School at the University of Texas at Austin, the Denton A. Cooley Centennial Professorship in Zoology at the University of Texas at Austin, the U. S. National Science Foundation, and the U. S. National Aeronautics and Space Administration. For considerable logistic support, we are indebted to the staffs of the Department of Zoology at the University of Western Australia and the Western Australian Museum plus the staffs of Conservation and Land Management, both at Kalgoorlie and at the Western Australian Wildlife Centre at Woodvale. Numerous Australians gave generously of their time and greatly assisted in this research effort. We thank two anonymous referees for suggestions that substantially strengthened this paper.

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