

A fire history of the savanna ecosystems in the Kruger National Park, South Africa, between 1941 and 1996

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This paper analyses the fire history of the Kruger National Park (1.9 million ha), South Africa, for different periods in the park's history, where fire protection was followed by prescribed burning and then a 'natural' (lightning) fire policy. Fires covering 16.79 million ha occurred between 1941 and 1996 (16% of the area burning each year on average). Of this area, 5.15 million ha was burnt between 1941 and 1957, when limited prescribed burning and protection from fire took place (16% burning each year on average). Between 1957 and 1991, 2213 prescribed burns covering 5.1 million ha (46.3% of the 10.98 million ha burnt during that period) were carried out. Lightning fires affected 2.5 million ha between 1957 and 1996, or 21.6% of the area. The mean fire return period was 4.5 years, with intervals between fires from 1 to 34 years. The distribution around the mean was not symmetrical and the median fire interval was 3.1 years. Some areas burnt more often than others, and mean fire return periods ranged from 2.7 to 7.1 years in the 11 major land systems of the park. Fires occurred in all months, but 59% of them took place from September to November. Prescribed burns were concentrated late in the dry season (September to November). Lightning fires were later, with 84.7% of the area burning between September and January. The implications of the analysis for the management of the park are discussed.

Savannas are tropical grasslands with scattered trees; they occupy about 20% of the land surface of the Earth, and 40% of Africa. These ecosystems are dynamic in their structure and composition, which changes in response to fluctuations in rainfall, levels of herbivory and occasional fires that burn through the grass swards. The role of fire in the maintenance of structure and function in African savannas is probably the oldest issue in savanna ecology¹ and remains contentious. In conservation areas, where early ideas were formed around equilibrium theory, fire was regarded first as something to be avoided, and was later applied at a fixed return period, when it was realized that fire was an integral part of the system. However, with the development of non-equilibrium theories of savanna dynamics, policy and practice in fire management have shifted towards burning under diverse rather than fixed conditions.^{2,3}

Fire management in the Kruger National Park has followed a similar trend. After the proclamation of the park in 1926, occasional and limited burning was used until 1948 only to provide green grazing for wildlife. Between 1948 and 1956, prescribed burning was stopped and firebreaks were established to assist in the control of wildfires. This policy was changed in 1957 to a formal system of burning once every three years in spring on

fixed management areas (termed 'blocks') ranging in size from 50 to 20 000 ha. In 1975, this policy was amended to allow for longer periods between fires in drier areas, with the season of burn varied between late winter, mid-summer and autumn.⁴ In 1992, the policy was again changed to one of allowing natural (lightning-ignited) fires to burn freely, but where prescribed burning would not be carried out, and all other fires of human origin were suppressed. For the sake of analysis, we recognized three periods in this paper. The period prior to 1956 was one of protection from fire, from 1957 to 1991, prescribed burning was actively practised, and from 1992 only lightning fires were permitted to burn.

The shift away from rigid prescribed burning on a fixed cycle was in response to several recent concerns. For example, Trollope and co-workers⁵ concluded that a dominance of grass species characteristic of poorly managed pastures and overgrazing was a result of 'excessively frequent burning'. In addition, there was concern over putative trends in woody vegetation structure.⁶ It appears (for example, from examining early aerial photographs) that large areas have been homogenized, possibly due to the rigid application of a policy of burning at three-year intervals. Tree densities have declined, greatly for some species, and this decline may be due to an 'unnatural' fire regime (in combination with other factors, such as browsing by ever-increasing numbers of elephants). In a revision of the research objectives for the park, developing an understanding of the attributes of natural fire regimes has been identified as a priority.

The Kruger National Park has a comprehensive set of fire records spanning five decades. These data have only partially been analysed. For example, the records for fires between 1980 and 1993 showed that most (90%) fires were of human origin, while lightning fires affected only 10% of the park. Lightning fires, however, took place in spring and summer (September to February), whereas other fires were predominantly in late winter and spring (June to October).⁷ While that analysis is useful, the available records span a much longer period and can also be evaluated spatially to provide information about the historical influences of fire on vegetation patterns and trends in the park.

This study reports on an analysis of fire patterns in the Kruger National Park based on fire records that date back to 1941, to quantify the nature of the fire regime that existed during the period of formal management. This record is probably the longest fire history for any savanna ecosystem in the world, and provides an important benchmark for interpreting the changes in vegetation structure that have taken place.

The study area

The Kruger National Park is situated in the low-lying savannas of the eastern parts of the Northern and Mpumalanga provinces of South Africa, adjacent to Mozambique in the east and Zimbabwe in the north (Fig. 1). The park was established in 1926, and covers 1 948 528 ha. Elevations range from 260 to 839 m

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above sea level. Mean annual rainfall varies from around 750 mm in the south to approximately 350 mm in the north (Fig. 2), but variations about the mean can be marked from year to year (Fig. 3).⁸ The pattern of rainfall over the past century has been characterized by extended wet and dry periods, in which the rainfall tended to be either higher or lower than the long-term mean for between 6 and 12 consecutive years (Table 1).⁹ These wet and dry periods have marked effects on the dynamics of the ecosystem, and on the occurrence of fires.

The park is crossed by seven perennial or seasonal rivers (the Crocodile, Sabie, Olifants, Letaba, Shingwidzi, Luvuvhu and Limpopo), which run from west to east. Geologically, the park can be divided into western and eastern halves. In the west, granites and their erosion products dominate, while the eastern sector is predominantly underlain by basalt, but includes the Lebombo Hills (primarily rhyolite formations) running from north to south. Two important areas of sandveld (on recent sands) also occur in the north, around Punda Maria and Pafuri.

Several studies have sought to classify the landscapes and vegetation formations of the park. One such study has divided the park into 35 'landscapes' based on geomorphology and vegetation.¹⁰ Another subdivided the park into 56 'land types' on the basis of soil and vegetation patterns and landform characteristics.¹¹ These land types were combined into 11 'land systems' on the basis of geological, geomorphological and climatic characteristics. The boundaries of these divisions have been captured on a geographic information system (GIS) and provided a framework for the examination of fire regimes in this study.

The flora of the park comprises 1983 species (N. Zambatis, pers. comm.), including over 400 tree and shrub species,¹² and over 220 grasses. Broadly speaking, there are four dominant vegetation types in the park. In the southwest, the low nutrient status of the soils results in a relatively low grazing pressure, and grass fuels accumulate during the growing season; rainfall is also higher, and as a result of these factors fires tend to be relatively frequent in these areas. The area is well wooded, and important tree species include the red bushwillow (*Combretum apiculatum*), knobthorn (*Acacia nigrescens*), tamboti (*Spirostachys africana*) and marula (*Sclerocarya birrea*). In the southeast, on basalt substrates, grasses are more palatable and tend to be heavily grazed. Important tree species include the knobthorn, leadwood (*Combretum imberbe*) and marula. North of the Olifants River, the granite areas in the west are poorly grassed; mopane (*Colophospermum mopane*) and red bushwillow are dominant trees. The northeastern areas on basalt are dominated by multi-stemmed mopane shrubs about 1 to 2 m in height.

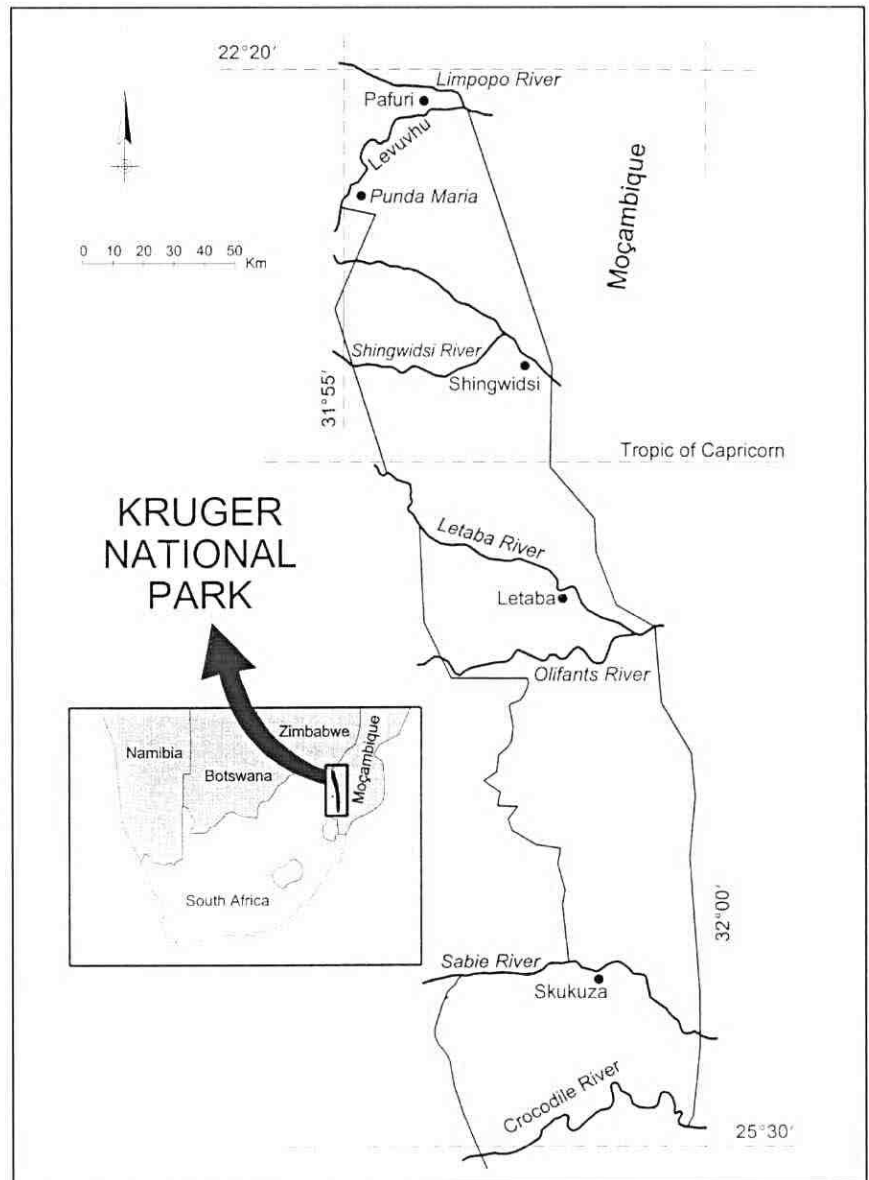


Fig. 1. Map of South Africa showing the location and topographical features of the Kruger National Park.

The fauna of the park is also diverse, including 147 species of mammals¹³ and 492 species of birds.¹⁴ Important herbivores include elephant (*Loxodonta africana*), buffalo (*Syncerus caffer*), impala (*Aepyceros melampus*), zebra (*Equus burchelli*), wildebeest (*Connochaetes taurinus*), waterbuck (*Kobus ellipsiprymnus*), kudu (*Tragelaphus strepsiceros*), giraffe (*Giraffa camelopardalis*), white and black rhinoceros (*Ceratotherium simum* and *Diceros bicornis*) and hippopotamus (*Hippopotamus amphibius*). Herbivory, particularly by grazers, has an important influence on fires through the consumption of grass fuels. In addition, browsing (particularly by elephants) has a strong impact on subsequent tree mortality after fires.

The fire record

Fires in the Kruger National Park were traditionally recorded in ranger's diaries prior to the introduction of a programme of prescribed burning in 1957. When prescribed burning was introduced, the park was subdivided into over 400 management areas, or 'blocks', ranging in size from 50 to 23 800 ha (mean = 4198 ha, Fig. 4). The boundaries of the 453 blocks that existed at

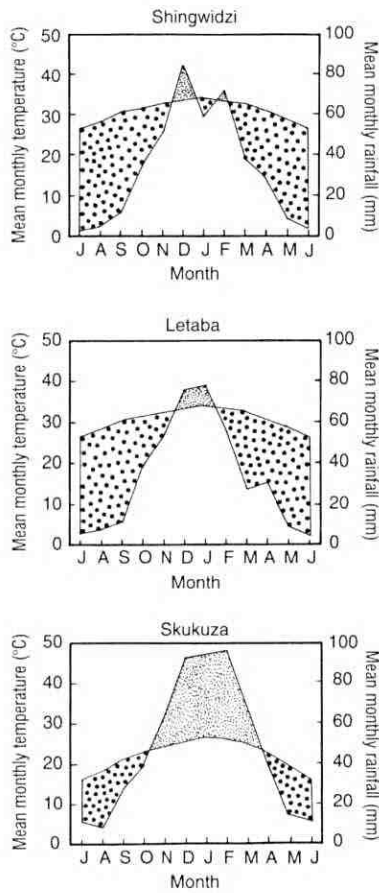


Fig. 2. Climate diagrams for three locations in the Kruger National Park (see Fig. 1 for the localities of stations).

the time of this study were captured on a GIS, and formed the basis of our analysis. The fire records for different periods were in three formats, as follows:

- (i) Sketch maps of the distribution of fires for each year from 1941 to 1956, available from a previous analysis of ranger's diaries.¹⁵ These were digitized, and overlaid on the boundaries of existing fire blocks to establish the percentage of the block that was burnt in each year. These fires were recorded at a coarse scale (1:500 000), resulting in partially burnt blocks only providing a crude estimate of percentage burnt.
- (ii) The board controlling the park took a decision to institute prescribed burning in fixed blocks on a three-year cycle in 1957.¹⁵ Fire records for each of these blocks, giving the dates and causes of fires, and in some cases an estimate of the percentage of the block that burned, were available from 1957 to 1991. These records were extracted from the management files for each block.

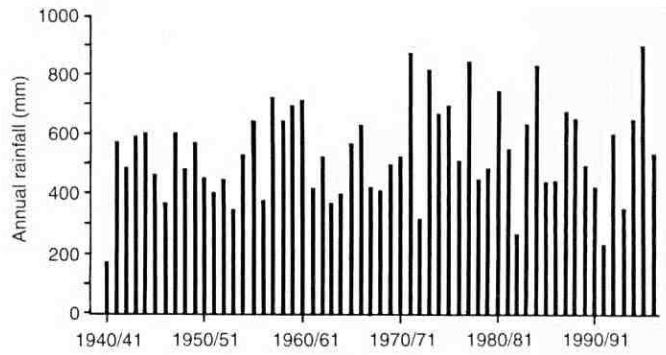


Fig. 3. Total annual rainfall at Skukuza, Kruger National Park, between 1940/41 and 1996/97. Data are for climatic years (1 July to 30 June).

(iii) As from 1992, all prescribed burns were stopped. Natural (lightning) fires were allowed to burn in line with a management policy, although other fires did occur. These fires were mapped (using fire reports and satellite images to establish boundaries on 1:50 000 topographical maps) and added to the database by allocating a date, percentage burnt, and cause of each fire to the existing fire management blocks.

Between 1957 and 1988, numerous adjustments were made to the boundaries of blocks. We established the extent and dates of these changes by comparing older maps to the existing set of blocks. Where necessary, fire records were re-allocated to the existing blocks by assigning the date of the fire and its cause, together with an estimate of the percentage of the existing block that would have burnt in that fire.

The cause of fires was recorded in seven categories: prescribed fires (where the whole block was intentionally burnt); firebreak fires (where the boundaries of the block were ignited under conditions where the fire would not progress very far, with the intention of creating a buffer strip — we refer to these strips as 'firebreaks' throughout); fires caused by lightning; escape fires (where prescribed or firebreak fires unintentionally spread to the block concerned, or where any fires originating outside the park burnt a block inside the park); other fires of human origin (poachers or trans-border migrants being the most common causes); other fires of known cause; and fires of unknown origin.

The fire record consisted of 5512 individual burns between 1957 and 1992, that burnt an area of 10.97 million ha. The total number of fires between 1941 and 1956 is not known (only the annual extent of fires was available), but during this period burnt 5.15 million ha. The period between 1992 and 1996 was initially characterized by a severe drought, and not many fires occurred. However, extensive lightning fires occurred in 1996, following good rains in 1995, burning 359 424 (50.4%) of the 712 055 ha burnt between 1992 and 1996.

Table 1. Cyclical patterns of rainfall from available recording stations in the Kruger National Park, showing the extent and duration of wet and dry periods between 1919/20 and 1992/93.⁹ The mean annual rainfall for all stations was 534.2 mm.

Dates	Number of recording stations	Length of period (years)	Type of period	Mean rainfall for period (mm)
1919/20–1924/25	1–2	6	Wet	650.2
1925/26–1935/36	3–7	10	Dry	462.3
1936/37–1942/43	8–11	6	Wet	590.1
1943/44–1952/53	9	9	Dry	510.6
1953/54–1960/61	9–14	7	Wet	586.4
1961/62–1970/71	14–17	9	Dry	457.5
1971/72–1981/82	17–19	10	Wet	638.7
1982/83–1994/94	19–27	12	Dry	450.0
1994/95–1996/97	29–34	2	Wet?	560.7

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Fig. 4. Distribution of management units ('blocks') which formed the basis for a spatial analysis of fire regimes in the Kruger National Park. See Fig. 1 for scale.

Data analysis

Estimation of percentage of block burnt

The 1137 records for individual fires between 1980 to 1993 were complete in terms of estimates of the percentage area of the blocks that burnt.⁷ Many (60%) of the fire records from 1957 to 1979 did not have these estimates; however, the cause of fires was consistently recorded. To fill in missing values of percentage burn, we assumed that firebreak burns (743 of the 4375 records between 1957 and 1979) burnt 20% of the block concerned, based on the estimates for fires from this source (firebreak burns were usually ignited to create a fuel-break around the periphery of the block, under conditions that would normally cause the fire to die out at night). Where more than one firebreak burn occurred in a block in the same year, we assumed that the total area of all firebreak burns that year was 20%, and reduced the estimates for individual burns proportionally.

For those records where the percentage area of the block burnt was recorded (73% of the 5512 fires between 1957 and 1992), a clear annual trend was evident. This trend was significantly correlated with annual rainfall five years earlier (Fig. 5). We used this relationship to estimate percentage burn for the fires where this was not recorded, excluding the firebreak burns (where we assumed that 20% of the area of the block was burned). In order to obtain an estimate, we first subtracted the extent of firebreak burns that occurred before the burn in question in the same year from the area of the block. We then used the relationship to estimate the proportion of the remainder of the block that would have burnt. Where more than one non-firebreak burn occurred

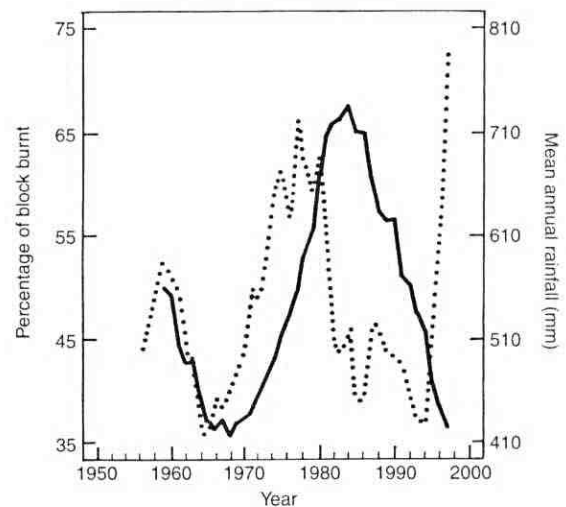


Fig. 5. Trends in percentage burn recorded in fires between 1957 and 1992 (5-year running mean, solid line), and annual rainfall (3-year running mean, dotted line). There is a significant relationship between percentage burn and annual rainfall five years before the fires ($y = 29.95x - 0.034$, where y is the percentage of the block burnt and x is the annual rainfall five years prior to the burn; $r^2 = 0.17$, $P < 0.012$).

in a block in the same year, we assumed that the total area of all non-firebreak burns that year was equal to the estimate, and reduced the estimates for individual burns proportionally.

Frequency of fires

Fire frequency was examined in three ways. First, where we wished to test for significant differences in fire return periods between areas of interest, the mean return period was calculated as

$$RP = \frac{(\sum i_j a_j)}{(\sum n_j a_j)}$$

where RP is the return period in years, j is the number of blocks in the area of interest, i is the inter-fire period in years, a is the area of block j , and n is the number of inter-fire periods (the number of fires minus 1). Using this method, we were able to test for differences between areas using one-way analysis of variance.

Secondly, where return periods were determined for short intervals, cases arose where only one fire had occurred in some blocks in the period concerned (that is, there was no inter-fire period on record). This precluded the use of the above formula, and we used $RP = y/(b/a)$, where RP is the return period in years, y is the number of years over which fires were recorded, b is the extent of all fires recorded over y years, and a is the area over which fires were recorded. In this case, only one number is produced, and it is not possible to test for the significance of any differences.

Thirdly, we estimated the frequency distribution around the mean by determining the period between successive fires in each block. To do this, we divided each block into 10 equal sub-blocks, and randomly assigned sub-blocks as burnt or not in each year based on the percentage burnt (i.e., if 20% of a block had burnt, two randomly selected sub-blocks were designated as having burnt). A key assumption in doing this was that each subdivision of a block had an equal chance of burning; this assumption was the only way to deal with the data, as the exact location of each fire within blocks with incomplete burns was not known. These data were used to determine the distribution of periods between successive fires in each block. To determine the distribution for the whole area being examined, we tallied the periods for all blocks, weighted by area.

We used maps of the land systems¹¹ and of rainfall to examine patterns of fire frequency. The rainfall distribution was derived from a national database that models rainfall from existing recording stations and topographical factors at a resolution of one minute by one minute.¹⁶ We also divided the data into different periods in order to determine the effects of climatic periods, and periods of differing management policies, on fire frequency.

Seasonality of fires

Seasonality of fires was examined monthly. The area burnt in each month was totalled for the area, time period, and cause. We used these data to establish whether seasonal differences in the proportion of area burnt varied between the land systems in the park, and between wet or dry periods. We also examined whether fires of different origin (particularly those started by lightning) differed in their seasonal occurrence.

Size of fires and extent of area burnt

The extent of fires was calculated from the area of the management blocks, and the estimates of the percentage of the block that burnt. These were then totalled for different landscapes, rainfall zones or time periods of interest (such as wet and dry climatic cycles, and periods of differing management policy). The estimation of the size of fires was constrained by the fact that fire records were kept for individual management blocks and not for individual fires. Thus, if a fire burnt over more than one block, this was not recorded. However, occurrences of the same fire burning in more than one block prior to 1992 were rare, as fires were almost always confined to a single block by effective backburning from the boundaries. For the fires that occurred after 1992, accurate maps of individual fires were available. We were able, in these cases, to estimate the areas of individual fires from these maps, using the areas of management blocks as a basis.

Fire climate

Climate and weather are important in determining the opportunities for fires to occur and spread, and together with fuel properties will affect their size and intensity. We obtained daily weather data from two representative weather stations in the park (Skukuza and Letaba, see Fig. 1) for the period 1981 to 1997, and used the U.S. National Fire Danger Rating System¹⁷ to calculate daily indices of fire danger. The data used included daily maximum and minimum temperature and relative humidity, cloud cover, rainfall duration and wind speed, and an estimate of the fuel composition and structure (we used fuel model L). Results are expressed in terms of a 'burning index', which can be related to the spread and intensity of a fire under prevailing conditions.

Effect of fuel load on the occurrence of fire

Grass biomass (fuel) estimates were defined from one to four points per management block for approximately two-thirds of the blocks in the park from 1989 onwards. These points were distributed across the whole park and all land systems, and were taken to be representative of fuel loads throughout the block. The single point (or in the case of blocks with multiple sampling points, the mean) biomass per block was determined for each year from 1989 to 1996. The annual occurrence of fire (other than in firebreak burns) in blocks was recorded as a binary variable — burnt or not burnt. The probability of a fire of any size occurring in a block in a given year was then estimated as a function of biomass using logistic regression.¹⁸

Results

Fire frequency

The mean fire return period for the entire dataset was 4.5 years. However, the distribution around the mean was not symmetrical (Fig. 6), and the median fire interval was 3.1 years. This indicates a skewed distribution in the data, with many short-interval fires, but a few areas experiencing relatively long intervals between fires, thus increasing the mean interval between them. Fires that burnt within one year of a previous fire accounted for 16% of the area burnt over the past 56 years; a further 17% of the area burnt within 2 years of a previous fire, and another 16% within 3 years (Fig. 6). Thus, for more than half a century, about half the area burnt within 3 years of the previous fire. About 80% of the area burnt within 7 years of the previous fire, and a small proportion (about 10%) burnt 10 years or more after the previous fire. As can be expected in a large and diverse area, the spatial distribution of mean fire return periods varied spatially (Fig. 7).

Mean and median fire return periods ranged from 2.7 to 7.1, and 1.8 and 4.6 years, respectively, in the 11 major land systems of the park (Table 2) between 1941 and 1996. The range of intervals between fires for the different land systems was from 1 to between 30 and 40 years. Most land systems had mean fire return periods of between 4 and 5.8 years, and two (the Klipkoppies and Phalaborwa systems) had mean fire return periods of 6 years or more. The median fire return period was generally shorter than the mean, and was much less for the Malelane system (1.8 as opposed to 5.3 years). Few areas (less than 1% of the Malelane land system to 10% of the Klipkoppies land system) managed to escape fire for more than 15 years (Fig. 8).

Rainfall has a marked effect on the production of grass fuels, and therefore on fire return periods. This was evident for areas that receive a mean annual rainfall of over 700 mm (Table 3). Here, the mean return period was 3.5 years, compared with around 5.2 years for areas with annual rainfall between 400 and 700 mm. Fire returns were longer in dry periods (where grass productivity, and hence fuel loads, would have been low) than in wet (Table 4). For the 10 years between 1971 and 1980 (a wet cycle, see Table 1), the mean return period was 4.3 years over the whole of the park. Over a similar period between 1983 and 1992 (a dry cycle), the corresponding period was 9.1 years. Mean fire return periods were similar between 1941 and 1956, prior to prescribed burning, and between 1957 and 1992, when prescribed burning was actively practised (5.9 and 6.2 years, respectively, Table 4). It would appear, therefore, that attempts at protection from fire did little to reduce fire frequencies. With the adoption of a policy of lightning fire, indications are that the

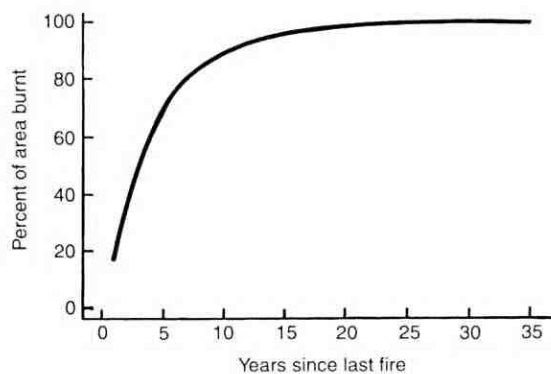


Fig. 6. The cumulative probability of fire in the Kruger National Park, calculated from fire records between 1941 and 1996.

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mean fire return periods have become longer. Because this policy has only operated for 5 years, we compared the mean fire return periods between 1992 and 1996 (where prescribed burning was not carried out, and lightning fires were allowed to burn) with a period of equal length and similar rainfall (1981–85). The mean return period under the lightning fire policy was 13.3 years, more than double that in the prescribed burning era (6 years, Table 4). This indicates that, for dry periods at least, the new policy could lead to longer intervals between fires.

Fire season

Fires occurred in all months of the year for the period of analysis (1957 to 1996), but most of the area (80%) burnt in the months from June to November (Fig. 9). September, October and November had the largest proportions of area burnt (23, 21 and 15%, respectively). Firebreak burns were conducted earlier in the year, with most (70% of the area) being carried out between May and July. Prescribed burns, which accounted for 43.7% of the total area burnt (see below), were concentrated late in the dry season, with 66.5% of the prescription-burnt area being burnt in the months of September, October and November. Lightning fires tended to be later in the year, with 84.7% of the area attributed to this cause burning between September and January. Other fires (most of which were of human origin) followed the same seasonal pattern as prescribed burns (80% of the area burning from July to November).

The seasonal distribution of fires was examined for the period when the lightning fire policy was in operation (1992–96). Here, a total of 712 031 ha was burnt in 5 years (Table 4). These fires were

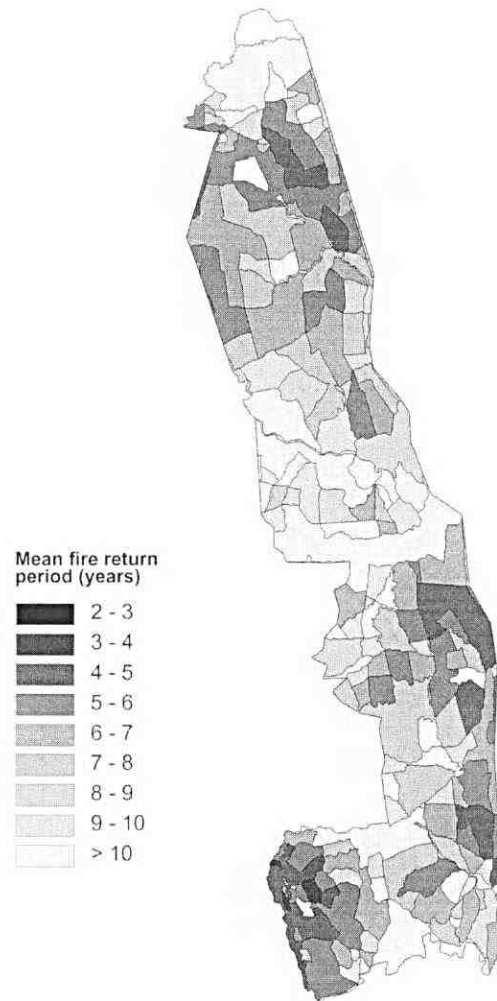


Fig. 7. Map of the Kruger National Park showing mean fire return periods calculated from fire records between 1957 and 1996. See Fig. 1 for scale.

Table 2. Fire return periods in 11 land systems (after Venter¹¹) in the Kruger National Park, South Africa, between 1941 and 1996. Means with the same superscript letter do not differ significantly at $P < 0.0005$.

Land system	Salient features	Area (km ²)	Extent of fires between 1941 and 1996 (km ²)	Fire return periods (years)		
				Mean	Median	Range
Malelane	<i>Combretum apiculatum</i> bush savanna on granite. Rainfall 600–700 mm/yr	400.3	5415	5.3 ^{ac}	1.8	1–34
Skukuza	<i>Combretum apiculatum</i> / <i>Terminalia sericea</i> bush savanna on granite. Rainfall 500–750 mm/yr	3742.6	35 496	4.2 ^{bd}	3.3	1–40
Satara	<i>Acacia nigrescens</i> / <i>Sclerocarya birrea</i> tree savanna on basalt and gabbro. Rainfall 500–650 mm/yr	2599.7	27 766	5.0 ^c	2.9	1–35
Vutome	<i>Acacia welwitschii</i> / <i>Euclea divinorum</i> tree savanna on Karoo sedimentary rocks. Rainfall 500–650 mm/yr	746.6	5767	5.8 ^c	3.8	1–39
Sabiepoort	<i>Combretum apiculatum</i> / <i>Pterocarpus rotundifolius</i> bush savanna on rhyolite. Rainfall 500–650 mm/yr	855.0	9362	4.1 ^{bd}	2.6	1–34
Phalaborwa	<i>Colophospermum mopane</i> / <i>Combretum apiculatum</i> bush savanna on granite. Rainfall 450–600 mm/yr	4981.9	40 521	7.1 ^e	3.4	1–32
Letaba	<i>Colophospermum mopane</i> bush savanna on basalt and gabbro. Rainfall 450–500 mm/yr	3418.2	29 884	4.4 ^{ad}	2.9	1–33
Bulweni	<i>Terminalia sericea</i> / <i>Combretum zeyheri</i> bush savanna on deep recent sands. Rainfall 450–500 mm/yr	395.3	2459	3.7 ^{bdf}	3.3	1–30
Klipkoppies	<i>Colophospermum mopane</i> / <i>Combretum apiculatum</i> tree and bush savanna on rhyolite. Rainfall 450–500 mm/yr	482.4	3457	6.1 ^{ce}	4.6	1–32
Nwamibiya	<i>Baphia massaiensis</i> bush savanna on recent sands. Rainfall < 400 mm/yr	508.1	3884	3.6 ^{bf}	3.4	1–35
Pafuri	<i>Colophospermum mopane</i> / <i>Burkea africana</i> tree and bush savanna on volcanic rocks and floodplains. Rainfall 400–650 mm/yr	861.7	3935	2.7 ^f	4.5	1–35
Total		18 991.8	167 947	4.5	3.1	1–40

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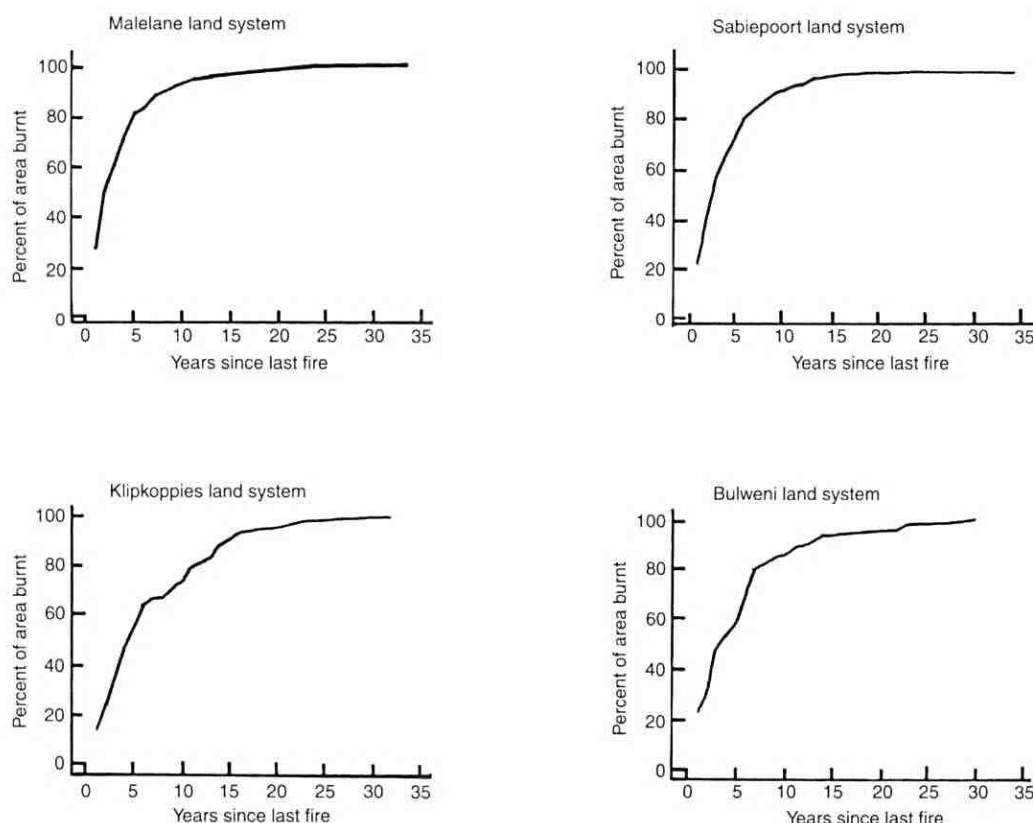


Fig. 8. The cumulative probability of fire in four land systems (see Table 2) in the Kruger National Park, calculated from fire records between 1941 and 1996.

concentrated in the three months from September to November, when 83% of the area was burnt (Fig. 10). We also examined a period of equal duration and similar rainfall (1981–85), when the policy of prescribed burning was in operation. Here, a much greater area was burnt (1.57 million ha), with 82% of the burns occurring over either an earlier or longer period (six months from June to November). The adoption of a lightning fire policy has therefore led to a discernible shift in fire season.

Size of fires and extent of area burnt

Fires covering 16.79 million ha occurred during the 56 years between 1941 and 1996 in the park. Of this area, 5.15 million ha burnt from 1941 to 1956, for which the records are not detailed enough to provide more than an annual total for each year. During the era of prescribed burning, 2213 prescribed burns were carried out, and these affected about 5.1 million ha (46.3% of the 10.92 million ha burnt during that period). There were also

Table 3. Fire return periods for zones of mean annual rainfall in the Kruger National Park. Means with the same superscript letter do not differ significantly at $P < 0.0005$.

Mean annual rainfall zone (mm)	Area (km ²)	Area burnt between 1957 and 1996 (km ²)	Mean fire return period (years)
400–500	6251	37 852	5.0 ^a
500–600	8663	54 919	5.3 ^b
600–700	2745	16 976	5.2 ^{ab}
700–800	314.6	1665	3.5 ^c
800–900	69.5	1238	3.5 ^c

Table 4. Mean fire return periods for wet and dry climatic periods, and for periods of varying management policies in the Kruger National Park (18 991.8 km²).

Period of analysis	Extent of fires (km ²)	Mean fire return period (years)
Wet climatic cycle (1971–1980)	44 149	4.3
Dry climatic cycle (1983–1992)	20 834	9.1
Limited prescribed burning and active fire protection (1941–1956)	51 541	5.9
Active prescribed burning (1957–1992)	109 750	6.2
Active prescribed burning (1981–1985)*	15 733	6.0
Lightning fire policy (1992–1996)	7120	13.3

*This period was chosen for a similar rainfall pattern to the period under which the lightning fire policy had been operative, for comparative purposes.

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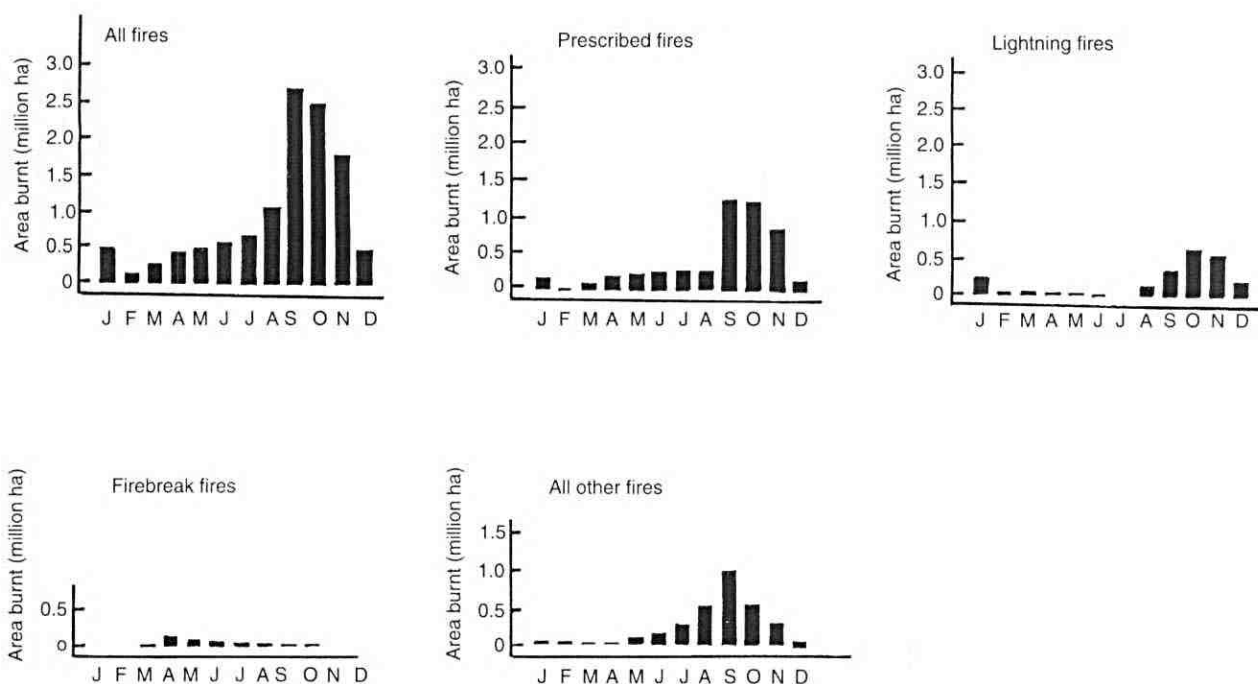


Fig. 9. Monthly distribution of total area burnt by different sources of ignition in the Kruger National Park between 1957 and 1996.

742 firebreak burns during this period, which affected an estimated total of 577 140 ha (see methods). Thus, formal management accounted for only 52% of the area burnt during this period. Lightning fires accounted for 2.5 million ha, or 21.6% of the area burnt between 1957 and 1991. Because these fires tended to occur later in the season, it can be assumed that their extent would have been greater if prescribed burning, which removed fuels that could have burnt in lightning fires, had not taken place. The balance of fires was caused mainly by poachers and refugees or were escape fires from burning operations.

Between 1957 and 1991, most fires were between 2000 and 4000 ha in size (Fig. 11A). Those more extensive than 10 000 ha burnt only 6% of the total area; the largest fire on record for this period was 18 110 ha. The period between 1992 and 1996 was characterized by 102 small fires of <10 000ha, and twelve really large ones (Fig. 11B). The large fires (>10 000 ha) accounted for 73% of the area burnt; four of these fires were greater than 30 000 ha in size (52 811, 75 396, 75 831 and 204 172 ha, respectively). These four fires all occurred in 1996, and were the largest fires recorded in the park's history.

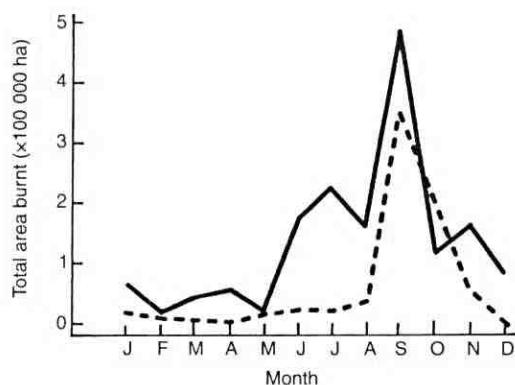


Fig. 10. Monthly distribution of area burnt in all fires under two fire management policies (lightning fires, dashed line, and prescribed burns, solid line) for two periods with similar rainfall (1981–85 for prescribed burning, and 1992–96 for lightning fires).

Fire climate

The mean burning index for each month at both of the stations analysed (Fig. 12) shows that conditions conducive to fires were highest during July, August and September, and lowest from December to March. Skukuza has higher mean burning indices as it experiences higher mean windspeeds than Letaba. Because the burning indices are mean (monthly) conditions, it is more useful to determine when extreme conditions occur, as are the times when large fires can be expected. Daily burning indices of greater than 50 (at Skukuza) and 39 (at Letaba) are in the top 5% of all values recorded at these stations. The occurrence of these conditions shows a far greater seasonal trend (Fig. 12). Such conditions occur frequently from June to October, and hardly ever between December and April (Letaba had higher occurrences in these months, as it is much drier than Skukuza, see Fig. 2).

The conditions that prevailed during the large fires of 1996 are of particular interest. These fires, in the south of the park, burnt between September 25 and October 5 of 1996. On these days, the burning index was always above 27, and exceeded 50 on three of the days. The park's managers contended that these conditions were unusual, and not likely to occur frequently. We determined that these conditions occurred at least once in 7 of the 16 years between 1981 and 1996 (Fig. 13). However, in at least 3 of these years (1989, 1992 and 1994), mean fuel loads (as determined in routine pre-fire surveys) were low (<2500 kg ha⁻¹, ranging from 1132 to 2128 kg ha⁻¹). Higher fuel loads were present in 1990 and 1991 (2740 and 2686 kg ha⁻¹, respectively), while in 1996 the mean fuel load was 3653 kg ha⁻¹. Estimates of fuel load were not available for the only other year in the period analysed that had extended periods of severe fire weather (1986, Fig. 13). While this analysis covers only a short period, it appears that conditions of severe fire weather that coincide with fuel loads in excess of 3500 kg ha⁻¹ are necessary for extensive (>30 000 ha) fires. The frequency of occurrence of such conditions over the long term is not known, but may be rare.

Effect of fuel load on the occurrence of fire

There was a significant relationship between grass biomass

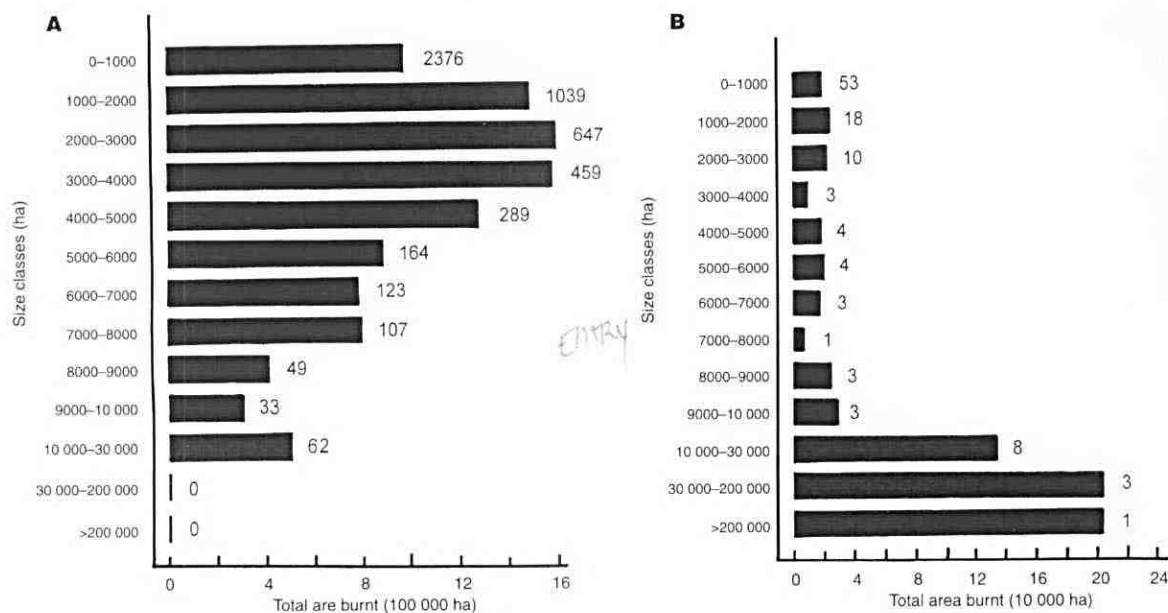


Fig. 11. Distribution of area burnt in fires of different size classes in the Kruger National Park. **A**, fires burnt between 1957 and 1991, when prescribed burning on fixed blocks was conducted; and **B**, fires burnt between 1992 and 1996, under a policy of lightning fires. The number of fires is shown next to the bars. Note the changes of scale for fires >10 000ha.

(fuel), and the probability of a fire occurring in any given block, and this relationship varied between years (Fig. 14, Table 5). The probability of a fire of any size occurring depends on grass biomass. The reason for the relationship differing between years may be due to the severity of fire weather, with the probability of fire increasing in those years where severe fire weather coincides with higher fuel loads. This is indicated in Fig. 14, where the probability of fire was higher in 1996 (a year with severe fire weather) than in 1995 (a year without such weather).

Discussion

The fire history in the Kruger National Park

There are many difficulties associated with constructing a fire history in ecosystems where long-lived trees that bear fire scars and annual rings are absent. As a result, detailed analyses of fire frequencies in such ecosystems tend to be rare. The lack of detailed analyses can lead to erroneous interpretations of fire frequency. This was the case in the Kruger National Park, where perceptions among managers were influenced by the mean fire return periods of around 7 years, based on analysis of data for 1980-1992.⁷ Because mean return intervals are normally calculated without considering the shape of the frequency distribution about the

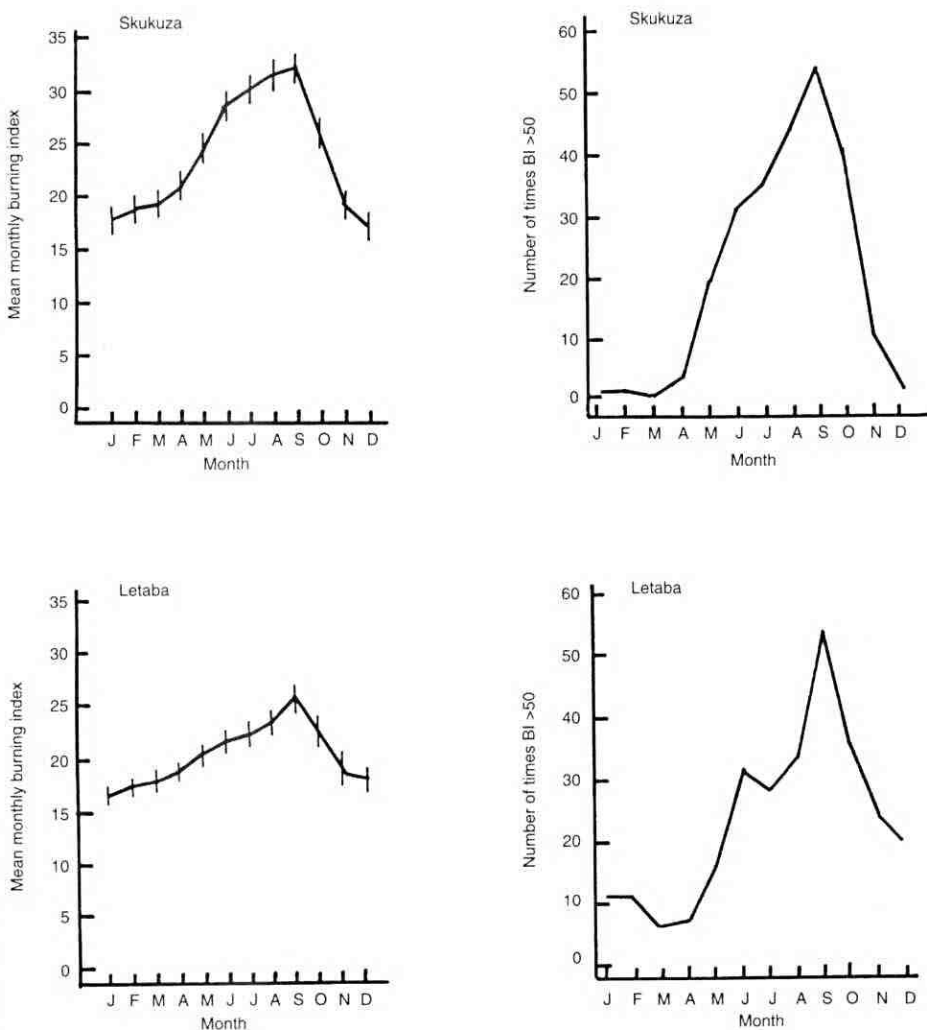


Fig. 12. Annual cycle of mean monthly burning index, and the number of days in each month that the burning index (BI) was in the top 5% of all values recorded, at two stations in the Kruger National Park. Data are for the period 1981-97; bars represent 95% confidence intervals of the mean.

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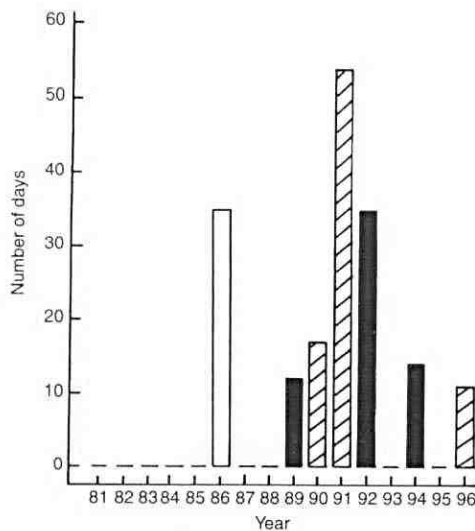


Fig. 13. The occurrence of extended periods (>10 days) of high fire danger (burning index >27 on each day, with at least three days >50) at Skukuza between 1981 and 1996. Shaded bars show years where conditions occurred together with high (> 2500 kg ha⁻¹) fuel loads. Solid bars indicate years when fuel loads were below 2500 kg ha⁻¹ (fuel estimates were not available for 1986).

mean,¹⁹ it was assumed that periods between fires were acceptably long. This study has shown that the return period between fires is much shorter than originally believed, as the median value for fire return period was well below the mean for most land systems. Concerns have recently been raised that the park has been burnt too frequently,⁵ resulting in deterioration of the grass sward and in relatively high mortality of trees. Our data support the notion that the park has been burnt frequently. Large areas of the park have been subjected to annual and biennial burns, and this could have important implications for the conservation of vegetation structure and biodiversity.

Fire season is another element of the fire regime that can have important biological effects. This analysis has shown that most fires take place in relatively rain-free winter months, when grasses are dormant and dry. However, there appears to be an important difference in seasonality between fires caused by lightning and other fires. Lightning fires tend to occur later in the year, and even in the period after the start of summer rains. Proponents of a policy of lightning fires (where lightning-ignited fires dominate) argue that the shift in fire season brought about by prescribed burning differs significantly from the regime under which the ecosystem evolved, and that this shift could have undesirable consequences. The effects of changes in fire season on grass species is relatively well understood,^{20,21} but the impacts on the balance between grass and woody species is less well understood and may be significant. This is one area where savanna ecologists could profit from an improved understanding of the physiology, reproductive biology and life history characteristics of the most important woody species. The lack of such knowledge has been identified as a conspicuous deficiency

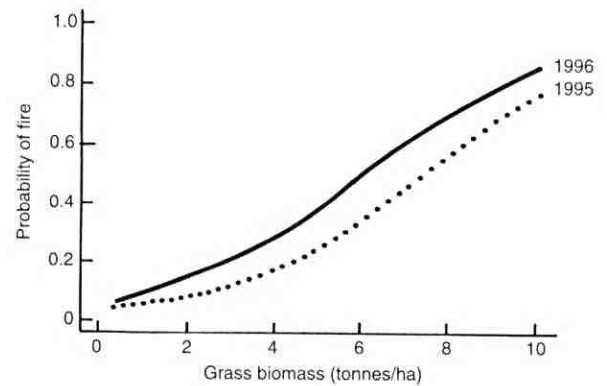


Fig. 14. The relationship between grass biomass (fuel) and the probability of fire in two individual years in the Kruger National Park. Severe fire weather conditions occurred in 1996, but not in 1995. The regression equations were $P(f) = e^Z / (1 + e^Z)$, where $P(f)$ = the probability of fire, e = the base of natural logarithms, and $Z = -3.47 + 0.00047b$ for 1995, and $-2.47 + 0.00051b$ for 1996 (b = grass biomass in kg ha⁻¹).

in the understanding of savanna dynamics,²² and will be needed to interpret the response of woody species to shifts in fire season.

Variation between and within land systems

The range of fire return periods varied almost threefold, from 2.7 to 7.1 years. The reasons for this variation are complex and related to the dynamics of the fuel layer and to sources of ignition. Fuel loads in savanna ecosystems are largely dominated by the grass layer; the grass biomass is a function of rainfall, soil fertility and herbivory.²³ Some examples of these interactions are discussed below.

The Malelane land system had the shortest median return period (1.8 years, Table 2). Here, relatively high rainfall and low fertility combine to produce a high biomass of grass. These grasses are seasonally unpalatable, and such areas are known locally as sourveld. Herbivory levels in sourveld are lower, and fire frequencies are consequently higher.²⁰ The true sourveld areas make up a smaller proportion of the Malelane and Skukuza land systems; these are described by Gertenbach¹⁰ as two landscapes that make up 846 km². Median fire return periods for both areas were 1.9 years. In addition to higher fuel loads, the areas are also on the boundary of the park, where additional sources of ignition and firebreak burning affect fire frequency.

The Satara land system has lower rainfall than the Malelane, but is characterized by relatively nutrient-rich, basalt-derived soils. Grasses in this area tend to be palatable throughout the year (a condition known locally as sweetveld), and herbivory levels are high. Despite lower rainfall and higher levels of herbivory, the mean fire return period does not differ significantly from that of the Malelane system. We attribute this to the ability of the fertile soils to produce good crops of grass in years of relatively high rainfall, which in turn support a similar number of fires to the Malelane system.

Table 5. Diagnostics of two logistic regressions giving the relationship between grass biomass and the probability of fire in the Kruger National Park in 1995 and 1996 (see Fig. 14).

Year	Estimates	Standard error of estimates	% deviance explained	Significance (<i>P</i>)
1995	Constant (-3.7)	0.4504	7.006	0.0004
	Biomass coefficient (0.00047)	0.000134		
1996	Constant (-2.47)	0.3539	13.358	<0.0005
	Biomass coefficient (0.00051)	0.000080		

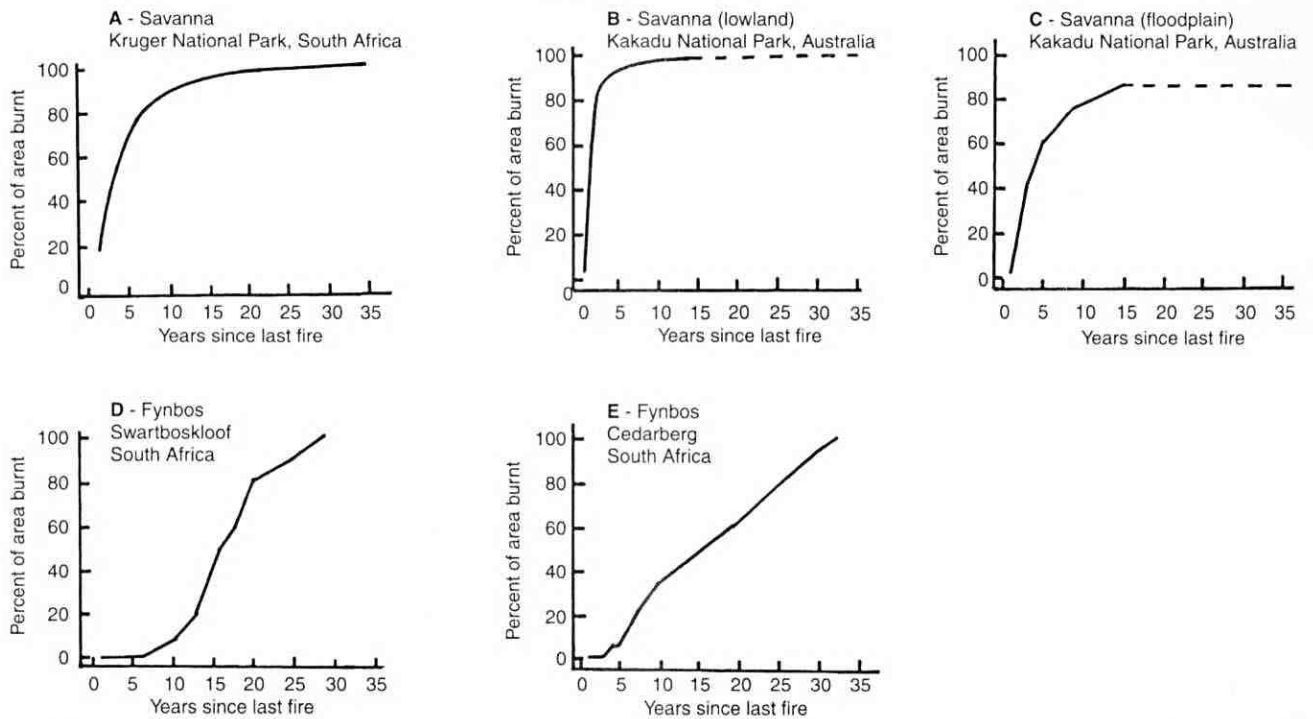


Fig. 15. The cumulative probability of fire in various ecosystems for which detailed fire histories are available. **A**, savannas in the Kruger National Park (this study); **B** and **C**, savannas in the Kakadu National Park, Australia;²⁵ **D**, fynbos shrublands at Swartboskloof;²⁷ and **E**, fynbos shrublands in the Cedarberg mountains.²⁶ Dashed lines indicate extrapolations beyond the available data.

The Phalaborwa (on granite) and Letaba (on basalt) land systems, north of the Olifants River, are dominated by mopane trees and shrubs. This species dominates on both granite and basalt, because of shallow soils underlain by impervious bedrock.²⁴ On basalts, grass biomass (and thus fuel) is presumably higher after good rains on the relatively fertile soils, which could explain the difference in mean fire return periods (4.4 and 7.1 years) despite similar rainfall.

Variation in mean fire return periods can be as great within land systems as between them. This can be seen in the mosaic of different return periods in adjacent areas (Fig. 7). The fact that these periods vary substantially between blocks with the same underlying geology and vegetation type, and the same climate and weather is probably due to differences in the dynamics of the fuel layer. This is probably a function of differential rates of herbivory. For example, Russell-Smith and co-workers²⁵ attributed a marked increase in fire frequency to increased herbaceous fuel loads associated with the removal of feral water buffalo in Kakadu National Park in Australia. Herbivory in turn is possibly related to the distribution of artificial water points. There are 611 boreholes and 129 dams in the park, and these have a strong influence on the spatial distribution of grazing pressure. The relationships between the artificial provision of water, herbivory, fire and feedback effects on vegetation dynamics are topics that need to be researched to be able to assess the consequences of ecosystem management in the area.

Comparison with other ecosystems

Detailed accounts of the fire history of savanna ecosystems are rare, but Russell-Smith and his co-workers²⁵ assembled a 15-year fire history for savanna vegetation types in the Kakadu National Park, northern Australia, from LANDSAT MSS imagery (Fig. 15). Here, fire frequencies were very high in lowland vegetation, with a median return period of less than 2 years. The floodplains at Kakadu, on the other hand, were characterized by less frequent fires, and a median return period of around 4 years. It

would appear, therefore, that fire frequencies in the Australian park were similar to those in the Kruger National Park. The Kakadu data were also analysed with respect to fire size; while the median fire size was <300 ha, some very large, late dry season fires (>400 000 ha) did occur. These are typical of uncontrolled, late dry season fires in the vast unpopulated expanses of northern Australia.²⁵ Such fires have not, until recently, been a feature of the Kruger National Park, as fires were confined to management blocks.

Fire histories are also available for several fynbos (shrubland) ecosystems from the mediterranean-climate areas of the Western Cape, South Africa.^{26,27} Here, fire return periods are longer (in the order of 15 years). A further feature of these ecosystems is that the distribution of fire return periods tends to be symmetrical around the mean (Fig. 15), so that median and mean values for fire return periods are similar. This indicates a normal distribution of return periods around the mean, as opposed the savanna systems which have skewed distribution. Fire return periods are also longer than for savanna, probably as a result of the coarser nature of fynbos fuels, coupled with slower build-up rates and less frequent occurrences of weather conditions conducive to large fires. The approach for depicting the distribution of fire return periods provides a useful descriptor of the fire regime in grasslands, savannas, and shrublands such as chaparral, fynbos, or heathlands. This is because fires in these ecosystems tend always to be surface fires burning in grass layers (for savannas and grasslands) or shrub canopies (in shrublands). In coniferous and boreal forests, on the other hand, the approach is less informative. In these ecosystems, fires can burn as low-intensity surface fires, or high-intensity crown fires, and these fires will have fundamentally different effects with the same frequency and return periods.

The management of fire regimes

The current fire management policy in the Kruger National Park allows 'natural' fires to burn freely. Prescribed burning is

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not carried out, and fires of human origin are extinguished. However, anthropogenic fires have been a feature of the last 35 000 years or more. Because lightning alone may not ignite sufficient fires to simulate the park in historical times, some consideration must also be given to allowing additional fires to burn. These would make up for fires that would have been started by man in the past, or those that would have entered the park from outside but are not now able to do so. Managers are required to contain fires that are not started by lightning, and it is assumed that the area burnt by non-lightning fires will be sufficient to make up for the additional fires that would have occurred in the past. Because of the uncertainty about the nature of the historical fire regime, managers will have to monitor the occurrence of fires, and base the need to intervene on the patterns of fire that establish themselves. The application of these principles is discussed in another paper.²⁶ The present analysis provides a benchmark around which rules can be developed to test whether an acceptable fire regime does eventuate. The indications to date are that some significant shifts have already taken place. The overall area that has burnt under the lightning fire policy is smaller, and the fires have been in the form of a few very large conflagrations, and relatively fewer small ones. Mean return periods between fires has increased, and there has been a shift in the occurrence of fire to later in the season. The degree to which these shifts can be accommodated will depend on their actual or predicted impacts. We suggest that managers draw up hypothetical thresholds to the distribution curves for fire frequency and season that can be taken as indicators of potential concern.²⁶ Fire records can be updated annually, using computer technology,^{29,30} and tested against these thresholds. In addition, managers can monitor trends in the plant and animal communities in the park. Any changes in the structure or composition of these populations or communities can be interpreted in terms of the fire regime and its history.

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