Fire management and research in the Kruger National Park, with suggestions on the detection of thresholds of potential concern

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This paper reviews the options for management of the savanna ecosystems of the Kruger National Park using fire. The major goals of management have shifted from attempts to use fire to achieve a stable vegetation composition, to one of recognising that savanna ecosystems are in constant flux. Fire is a major form of disturbance that helps to maintain a state of flux, and thus to conserve biodiversity. Three candidate approaches for fire management have been put forward—the lightning fire approach, the patch mosaic burning approach, and an approach based on the assessment of ecological criteria. These approaches differ in their underlying philosophies, but not necessarily in their outcomes, although this cannot be predicted with confidence. We propose, therefore, that patterns of fire frequency, season, intensity and spatial distribution be recorded and monitored, and that these patterns should serve as surrogate measures of biodiversity. Guidelines for the definition of thresholds of potential concern with regard to these patterns are discussed. The monitoring of both fire patterns and trends in plant and animal populations can be used to identify interactions between fire and the components of the ecosystem, and these in turn can be used to define a relevant research agenda. The role of management in monitoring and assessing fire patterns (previously regarded as a research responsibility) is emphasised. Convergence in the patterns of fire that result from the different management approaches could also serve as a basis for merging some or all of these approaches in order to simplify management.

Keywords: fire, management, savanna, research, monitoring.

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Introduction

The various approaches to fire management in the 1.9 million ha Kruger National Park over the past 70 years have reflected the evolution of an understanding of the role of fire in savanna ecosystems. The practices since the park's proclamation in 1926 have included the "indiscriminate" application of fire to improve grazing, fire exclusion, prescribed burning on fixed and flexible rotations, and a policy of natural burning (in that order) (Joubert 1986; Van Wilgen *et al.* 1990; Trollope *et al.* 1995). These policies have followed similar trends elsewhere in southern Africa (Mentis & Bailey 1990; Du Plessis 1997). The current policy (introduced in 1992) calls for allowing natural (lighting-ignited) fires to burn freely, but where prescribed burning will not be carried out, and fires of human origin will be suppressed.

The historic fire regime in the Kruger National Park is relatively well known (Trollope 1993; Van Wilgen *et al. in press*). Fires covering 16.79 million ha occurred between 1941 and 1996. Of this area, 5.15 million ha burnt between 1941 and 1957, when limited prescribed burning and protection from fire took place. 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 burnt 2.5 million ha between 1957 and 1996, or 21.6% of the area burnt during that period. The mean fire return period was 6.3 years, with intervals between fires from 1–40 years. Fires occurred in all months, but prescribed burns were concentrated in early spring (September to November), at the end of the dry season. Lightning fires were later, with 84.7% of the area burning between September and January.

The prior policy of prescribed burning on a three-year cycle was introduced in 1957. The official view at that time called for the policy to continue "until such time that it is proved incorrect" (Joubert 1986). At the same time, a comprehensive burning experiment was initiated to investigate the effects of fire (Van der Schiff 1958). This experiment included the application of annual, biennial and triennial burns in different seasons on plots located in the major landscapes of the park. The experiment was expanded in the late 1970s (Gertenbach & Potgieter 1979), and the application of treatments has continued to the time of writing (1997). The data collected during the course of this experiment have not been analysed, other than in isolated papers of limited scope (Van Wyk 1971; Trollope & Potgieter 1985; Trollope *et al.* 1996a).

The prescribed burning policy remained in place, with some adjustments, until 1992. At that stage, a number of concerns were raised, which resulted in a change in policy from active prescribed burning on a fixed cycle, to one of moving towards a more flexible and variable pattern of burning. This change was in line with the development of non-equilibrium theories of savanna dynamics, which advocate burning under diverse rather than fixed conditions (Mentis & Bailey 1990; Walker 1989). The specific concerns included:

(i) The observation that a dominance of grass species characteristic of poorly managed pastures and overgrazing ("increasers") was a result of "excessively frequent burning" in combination with severe drought (Trollope *et al.* 1995);

(ii) Putative trends in woody vegetation structure (e.g. Viljoen 1988). It would appear (for example, from examining early aerial photographs) that large areas have been homogenised, possibly due to the rigid application of a policy of burning at three-year intervals. The density of larger trees has declined, dramatically for some species, and this decline may be due to a regular fire regime with short-interval fires (in combination with other factors, such as browsing by elephants);

(iii) The practice of 'ringburning" associated with prescribed burning. This refers to the process where fires are ignited around the periphery of management blocks and allowed to burn towards the middle. More natural fires, for example those associated with lightning strikes, would spread out in all directions from a point, allowing the fire to develop a range of intensities as it spread. Ringburning can prevent animals from escaping from fires, and also leads to a disproportionately large area burning as a high-intensity headfire (an effect magnified by the fact that these fires are carried out during the day, and never at night); and

(iv) The lack of variation associated with burning on a fixed cycle. This includes such things as occasional longer periods

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between fires, or varying the size of fires, on the assumption that such variation will promote the conservation of biodiversity (see, for example, Hansson 1997; Wiens 1997).

In attempting to select an appropriate fire management approach for the Kruger National Park, discussions have focused on the definition and nature of a natural fire regime. This is required by the mission statement, which calls for the maintenance of biodiversity "in all its natural facets and fluxes" (Anon 1997). There has been considerable debate about the best approach to adopt in order to achieve such a regime, which could be expected given the difficulties in defining what qualifies as "natural". Three candidate approaches for fire management have been put forward—these are the lightning fire approach, the patch mosaic burning approach, and an approach based on the assessment of ecological criteria (see below).

This paper explores the essence of the proposed fire management approaches, to examine if, and how, they differ in terms of the outcomes they will deliver. We propose guidelines for developing thresholds of potential concern with regard to the fire patterns that establish themselves in the application of the three management approaches. We provide a brief account of sets of conditions that could guide decisions on whether to discontinue any of the management options, as well as the future of fire-related research in the light of the new management approaches.

The definition of natural fire regimes

The policy of attempting to restore a natural fire regime to the Kruger National Park has been adopted to allow those processes under which the ecosystem evolved to continue operating. Similar attempts have been made elsewhere, particularly in the United States where a strong "wilderness" lobby has driven such policies in a range of National Parks (Kilgore & Heinselman 1990). Parsons & Van Wagtendonk (1996) have defined the goal of such a fire management programme as "to preserve, or where necessary restore, fire as a natural ecosystem process". These authors point out that this goal will be accomplished when fires of similar size burn at similar intervals, intensities and seasons, and thus with similar ecological effects, as fires that burned in the past or that would have occurred today had (modern) humans not intervened.

There are a number of dangers inherent in allowing a system of supposed natural fires to operate unimpeded. The first, and perhaps most obvious, is that the parameters of a natural fire regime are not known and probably not knowable—we therefore cannot be sure that the regime that results is in fact natural. Secondly, processes can only operate naturally when the factors that control them are unaltered from a pristine state (Bonnicksen & Stone 1982). It can be argued that the Kruger National Park is a highly modified environment. It is entirely fenced, restricting the migration of herbivores and thus impacting on the dynamics of both grass fuels and woody plants. Many artificial water points (611 boreholes and 129 dams) have allowed new patterns of herbivory to develop within the boundaries of the park, further impacting fuel loads. Historic programmes of prescribed burning, and culling, have influenced the structure and composition of the ecosystem, and its fuel properties. Development outside of the park has changed the patterns of fires that previously burnt across the (artificial) park borders, while within the park a network of roads and other infrastructure affects fire patterns. Finally, man has played a role in the ecology of Africa, through the use of fire, for a very long time—longer than on any other continent. The degree to which this can be regarded as natural, and the means by which to simulate a mix of lightning and anthropogenic fires, are not known.

Assuming that the characteristics of a natural fire regime could be defined, a number of other questions remain. These include whether a particular management approach would simulate the desired regime, and if it did not, how it would differ in terms of the fire patterns that established themselves. Secondly, the problem of unplanned fires, particularly those started by humans, is so large that any fire management approach has to develop a means of incorporating such unplanned fires into decision processes. The candidate management approaches are outlined in the section below.

The proposed fire management alternatives

Lightning fire approach

This policy, also termed a "wilderness", or *laissez faire* approach by Trollope *et al.* (1995), is aimed at simulating a fire regime that would be similar to the one that existed in the park prior to intervention by modern man, and one to which the biota of the park would be best adapted. The approach calls for allowing natural (lighting-ignited) fires to burn freely, but where prescribed burning will not be carried out, and fires of human origin will be suppressed. Because lightning alone may not ignite sufficient fires to simulate a "natural" regime, some consideration has to be given to allowing additional fires to burn. These would make up for fires that would have been started by early man, or those that would have entered the park from outside, but are not able to do so due to modifications or suppression outside of the park. Managers will be required to suppress fires that are not started by lightning, and it is assumed that the area burnt by these (non-lightning) fires will be sufficient to make up for the additional fires that would have occurred in the past. This approach has been followed for almost 6 years, and has apparently resulted in some shifts away from patterns that characterised the historic fire regime in the park (Van Wilgen *et al., in press*). These include a smaller total area burnt (resulting in longer mean fire return periods), a shift in season to later in the year, and a shift in fire size distribution to include a number of very large fires.

Patch mosaic burning

This approach (B.H. Brockett *pers. comm.*) aims to establish a mosaic of vegetation structural types, by applying a large number of fires over an extended period within each year. The assumption is that the heterogenous mosaic that results from the application of such fires will be the most efficient means of conserving biodiversity. The system is applied by determining the grass biomass in April of each year. The percentage of the area to be burnt is determined as a function of biomass, and ranges from about 5% of the area for a biomass of 1500 kg/ha, to 50% for a biomass of 7000 kg/ha or more. The number of fires in which this area will be burnt is a function of the percentage, and ranges from a target of 6 fires per 50 000 ha in cases where only 1% of the area will be burnt, to a target of 40 fires per 50 000 ha in cases where 50% of the area will be burnt. These fires are then distributed over the available months between April and November. Fires are ignited at random points, and allowed to burn out by themselves. Once the target area allocated to each month falls between defined limits , no further fires are ignited until the next month. Because the initial fires are put in early, before conditions that would lead to extensive fires have begun, initial fires tend to be smaller. Once conditions that would allow for fires to spread over large areas set in, the fires are prevented from becoming too large as they burn out against earlier, smaller burns. The net result is a mosaic of burns of different sizes, burnt under different conditions and in different seasons. This method has been successfully used in the Pilanesberg National Park (50 000 ha) and elsewhere, and could be applied to similar-sized subdivisions within the Kruger National Park (for example, a ranger section).

Ecological criteria assessment

This system was developed in response to the concern that excessively frequent burning and severe drought had led to a deterioration in the grass species composition in many areas of the Kruger National Park (Trollope *et al.* 1995). Under this system, the decision of whether to burn or not is based on an assessment of grass biomass and the species composition of the grass sward, and the area already burnt in accidental fires. An upper limit of 50% of sourveld and 33% of sweetveld areas for any burning is set; if this has already burnt in accidental fires, no further burning should be considered. If this is not the case, then areas can be burnt, up to this limit, provided that they have a grass biomass of greater than 4 000 kg/ha, and provided that grasses classified as "increaser II" species (see Van Oudtshoorn 1992) are not dominant in the sward. Fires that start accidentally in an area that meets the criteria for burning can be allowed to burn, or, in cases where the criteria are not met, such fires should be suppressed. Fires could be applied as point ignitions, rather than ringfires, and will require the maintenance of a network of firebreaks around management units (termed "blocks"). This system has been described, but has not yet been applied in practice.

Comparison of the three approaches

Each of the management approaches above will possibly result in a characteristic fire regime, which can be measured in terms of the frequency, season, intensity, size class distribution and spatial distribution of fires (Table 1). Each will presumably also have an associated set of ecological effects, many of which will be difficult to predict. This difficulty is both due to a limited understanding of the impacts of fire on all elements of the ecosystem, and the fact that fire cannot be considered in isolation from other factors such as herbivory and variation in rainfall. It should also be borne in mind that, in practice, none of these approaches will operate on its own; unplanned fires, both of human or natural (lightning) origin, will continue to form an important part of the fire regime, and any approach that is adopted will have to take this into account (although the patch mosaic system may limit the impact of unplanned fires by breaking up continuous grass fuels in early burns)

The main differences between the three proposed approaches will be found in their underlying philosophies. The lightning fires approach follows a "nature-knows-best" philosophy, and no goals are explicitly set with regard to the amount and distribution of fires that should take place. The patch mosaic approach is essentially driven by the assumption that fire patterns are effective surrogate measures of biodiversity (see below). It actively seeks to establish a heterogeneous mosaic of vegetation structure by applying a range of fires in different seasons, assuming that this is a good way to conserve biodiversity. It is explicit in its goals with regard to area and seasonal distribution of fire. The use of ecological criteria starts with a goal of driving the system towards a desired distribution of vegetation structure and composition through the use of fire. It is therefore explicit in terms of measures such as grass species composition and fuel loads; fire frequencies and season would be selected to achieve a desired result based on the best knowledge about the response of the biota to fire, and are not goals in themselves.

The outcomes of each of these approaches are not readily predicted, but can in some cases be based on experience (Table 1). An analysis of fire regimes in the Kruger

Table 1 (across two pages)

Salient features of the most likely outcomes (in terms of measurable features of the
Note that prescribed burning on a three-year cycle is no longer being considered as

	Prescribed burning on a three-year cycle	Lightning fires
Basic philosophy of approach	Regular fire is necessary to improve the quality of grass forage.	Lightning fires should produce the same patterns of frequency, season and intensity that characterised the regime under which the park's biota evolved.
Fire frequency	Mean fire return period of 6 years and median of about 3 years. Small areas survive without fire for up to 30 years. Supposed greater regularity of intervals between fires.	Mean fire return period of about 10 years and median of about 5 years.
Fire season	Can be chosen as desired. In the past 66% of area burnt in September, October and November.	Fires in the late dry or early wet season (85% between September and January).
Fire intensity	Relatively high due to ringburning.	A range of intensities will be achieved.
Fire size distribution	Most (70%) of fires smaller than 6000 ha. Largest fires equal to the size of the largest block (about 18 000 ha).	Some small fires, but fires tend to be larger. Very large fires (> 200 000 ha) possible after good rains.
Relative spatial distribution of fires	Coarse matrix of evenly distributed fires.	Coarse matrix of unevenly distributed fires.
Logistics and costs	Relatively expensive in terms of the maintenance of a network of firebreaks. Some wildfires have to be suppressed.	Low maintenance costs, but many wildfires of human origin may have to be suppressed. Risk of high fuel buildups around camps or other infrastructure.
Ecological effects	Frequent burning in dry periods leads to dominance by "increaser" grasses and a decrease in the diversity of perennial grasses. Homogenization of woody vegetation structure over large areas?	Longer periods between fires will favour woody species? Large fires, if followed by drought, could reduce available forage and increase herbivore mortality.

fire regime) of four approaches to fire management in the Kruger National Park an option, but is included here for comparative purposes

Patch mosaic burning	Assessment of ecological criteria
Patch mosaic burning should result in a heterogenous vegetation structure at a fine scale, and thereby maximise biodiversity	Given that the desired composition, structure and dynamics of the vegetation are known, a fire regime can be selected to produce that vegetation.
Mean fire return periods of about 4 years; median about 2–3 years.	Mean fire return period of about 8 years and median of about 4 years.
Fires begin early (May) and continue until the end of November. A greater proportion is burnt earlier following years of higher rainfall.	Can be chosen as desired.
A range of intensities will be achieved.	A range of intensities can be achieved if ringburning is not applied.
Mosaic of small and relatively large (up to 10 000 ha?) fires, but no very large fires.	Most (70%) of fires smaller than 6000 ha. Largest fires equal to the size of the largest block (about 18 000 ha).
Fine matrix of evenly distributed fires.	Coarse matrix of evenly distributed fires.
Low cost and lower risks of wildfires and fuel buildups. However, random ignition points may be difficult to reach in large undeveloped areas.	Relatively expensive in terms of the maintenance of a network of firebreaks. Some wildfires have to be suppressed.
Diversification in vegetation structure. Increase in biodiversity?	Dominance by "decreaser" grasses and improved quality of grazing. Opportunities for trees to develop to large sizes if fire excluded for longer periods?

Table 2 (across two pages)
Examples of causes of potential concern related to fire, their significance for the conservation of

Cause of potential concern	Method of measurement	Significance of element for conservation of biodiversity
Fires do not develop variable long-term patterns with respect to frequency.	Curve of probability of fire over past 30 years.	A range of fire return periods will maximize diversity. Frequent fires promote grasses, while infrequent fires promote trees and shrubs.
The risk that burning may be followed by drought	Proportion of area burnt in each month as the fire season progresses.	Burning removes forage and cover which, if not replaced by new growth, can lead to excessive mortality of herbivores.
The seasonal distribution of fires does not approach the desired distribution.	Proportion of area burnt in each month over the past 20 years	Most plant species can survive fires in the dry season when they are dormant. Late season or summer burns detrimental to "decreaser" grasses and/or to tree Continual concentration of successive fires in the same season could reduce diversity.
The range of fire intensities is too narrow.	Estimates of the dominant intensity over the past 10 years of each fire based on fuel consumption and tree scorch height.	Intense fires a major cause of tree mortality. Possibly important for germination of soil-stored seed.
The extent of fires in any year should be within reasonable limits.	Proportion of area burnt in the past 12 months	Lack of fire over large areas allows too much of the grass sward to become moribund. Extensive fires in the same year reduces refuge, forage during droughts, habitats for certain species.
Extremes in fire size distribution may lead to undesired effects	Size of individual fires over the past 10 years.	Smaller fires tend to concentrate herbivores. Very large fires may affect dispersal or colonization opportunities.
Cause of fires.	Recording of cause of fire.	No biological significance?

biodiversity and suggestions for thresholds of potential concern

Thresholds of potential concern (TPCs)	Rationale
Shifts in median fire return period; range of post-fire age for the 20% of the area with the greatest post-fire age; and the maximum post-fire age (see Fig. 1).	Correction of trends towards extremes in fire frequency.
Proportion of the area burnt in each month should not exceed limits in Fig. 2.	Risk of failure of rains can be more accurately predicted as season progresses.
Ratio of area burnt in winter/early spring to that burnt in late spring/summer should be between 2.25:1 and 1.75:1.	Biota adapted to dry season fires, but occasional early wet season/summer fires needed to enhance diversity.
The proportion of high, moderate and low intensity fires to be in the range of one quarter to half of all area burnt.	A range of intensities will promote diversity.
Calculate desired thresholds from grass biomass at the start of the fire season (see Fig. 3). TPC is reached if the area burned is above the upper limit or below the lower limit.	Fire occurrence should be kept within appropriate limits to provide a mix of habitats, and to prevent either excessive bush encroachment or deterioration of the grass sward.
Dominance of either large or small fires (Fig. 4).	A range of fire sizes promotes diversity.
Unplanned fires of human origin should not exceed 25% of all fires.	Exceeding this limit indicates lack of management ability to control or direct fire regime appropriately.

National Park over the past 56 years (Van Wilgen *et al. in press*) has given some indication of the outcomes that should result from prescribed burning on fixed rotations, or from lightning fire (although the latter has not been implemented for long enough to draw confident conclusions). The patch mosaic system has been implemented at the Pilanesberg National Park for 9 years, and the outcomes in Table 1 are based on experience there. The approach of using ecological criteria has not been implemented, making the estimates of outcomes speculative at this stage. However, it has been suggested (based on a retrospective assessment, Trollope *et al.* 1996b) that the frequency of burning in the Kruger National Park would have decreased by "over half" if burning had been conducted according to veld condition based on key grass species (Trollope 1990).

Thresholds of potential concern

Definition

The change in fire policy has accentuated the need for monitoring systems to identify any effects on biodiversity which may approach what have been termed "thresholds of potential concern" (TPCs). These have been defined as "those upper and lower levels along a continuum of change in a selected environmental indicator which, when reached, prompts an assessment of the causes which led to such an extent of change, and results in either (a) management action to moderate such causes, or (b) re-calibration of the threshold to a more realistic or meaningful level" (Anon 1997). Such thresholds are being defined for a wide range of biotic and abiotic ecosystem descriptors, and will underpin a comprehensive monitoring system in the park.

Because of the complexity involved in measuring biodiversity (e.g. Noss 1990), an approach of using surrogate measures is proposed here. Surrogate measures would track changes in measurable components of the ecosystem, and identify thresholds of potential concern in terms of impact on biodiversity. While biodiversity in all of its forms is complex to measure or monitor, the progress of a fire management plan towards stated goals will be easier to monitor. This approach has been proposed for fynbos ecosystems (Van Wilgen *et al.* 1994), and could be applied in savanna ecosystems as well.

Using the fire regime to define thresholds of potential concern

The term fire regime is used to describe the combination of frequency, season and intensity of fires that characterise a particular area. Fire frequency is the reciprocal of the time between fires. Season refers to the time of year that fires occur, particularly in relation to the growth state of plants. Fire intensity is a measure of energy release in fires, which varies (in similar fuel complexes) with the moisture, wind and slope conditions under which the fire burns. Fire type (sometimes regarded as an additional element of the fire regime) will also affect fire intensity. Fire type distinguishes between headfires (fires burning with the wind or upslope) and backfires (fires burning against the wind, or downslope), as well as between ground fire (fires burning in organic layers of the soil), surface fires (fires in the lower vegetation strata) and crown fires (fires in the canopies of trees). For practical purposes, savanna fires are all surface fires, burning in the grass layers below the trees, but they vary as head or backfires. The size and spatial arrangement of fires is another important aspect that should be considered, as it has ecological implications. Ignition sources are not seen as being significant elements of the fire regime in themselves, although some patterns of frequency and season may be associated with certain sources of ignition.

None of the above measures is a constant; they vary at the same place in or between successive fires. Such variation is important in maintaining biodiversity and the co-existence of species (Van Wilgen *et al.* 1994; Yeaton & Bond 1991). The mean, and the distribution around the mean, for the frequency, season, intensity and size of fires in an area would be needed to provide a complete picture of a fire regime. This distribution, rather than a fixed value for each measure, would constitute the surrogate measure of biodiversity that could serve as a goal for fire management programmes. Limits to this distribution, that would signal the potential elimination of any species from the community (or undesirable shifts in community structure) would constitute thresholds of potential concern. The various potential TPCs (Table 2) are discussed below.

Fire frequency

A long-term assessment of fire frequency can be obtained from a curve of fire probability, derived from successive fire records for an area (see Van Wilgen *et al.*, *in press*). Shifts in the shape of this curve (Fig. 1) will indicate either an increase or decrease in the mean, median and maximum fire return period. Thresholds for acceptable limits for both of these variables will differ for the different landscapes of the park, and will need to be set for such landscapes. In addition, these curves can indicate whether or not an acceptable degree of variation is being achieved with regard to fire frequency. Here, targets

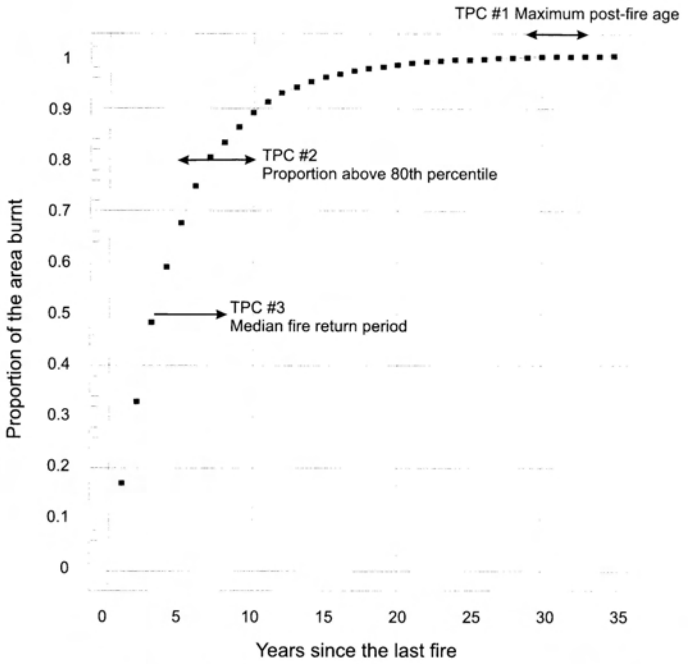

Fig. 1. The cumulative probability of fire, showing proposed thresholds of potential concern relating to the pattern over the 30 years prior to evaluation.

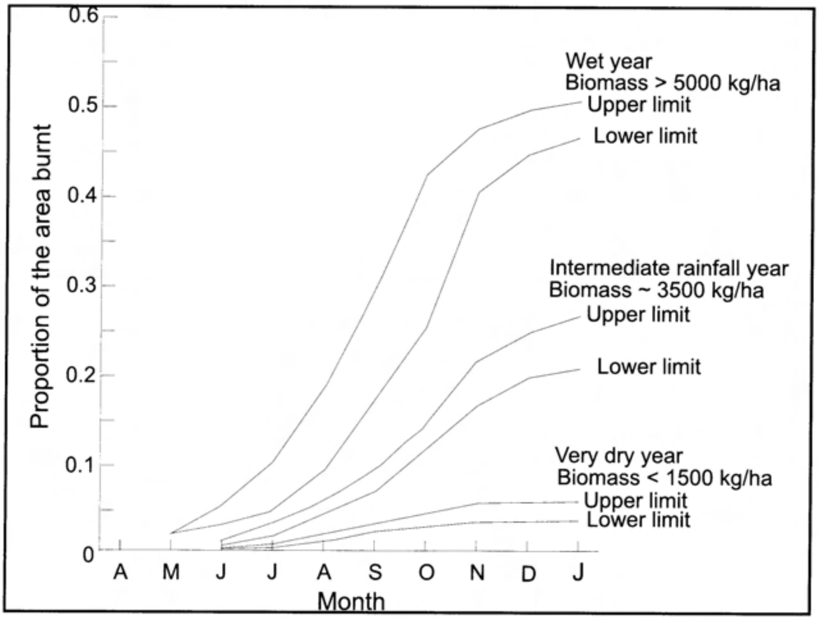

Fig. 2. Proposed thresholds of potential concern relating to the cumulative area burnt per month within a single fire season.

can be set for the proportion of the area that escapes fire for longer than a given time (which again should vary between landscapes). For example, small proportions of any area may need to escape fire for longer periods so that trees can establish, or switch from fire-suppressed "Gullivers" (Bond & Van Wilgen 1996) to trees of large stature.

Burning, drought, and forage availability

Fire followed by drought can lead to shortages of forage for grazing animals, where the consequences can be severe if burnt areas are extensive. For this reason, managers may be concerned if extensive areas are burnt early in the fire season, when the likelihood of drought is less predictable. Thresholds of potential concern can be defined in terms of time to the onset of the rain season, and can be made to vary according to grass biomass. Grass biomass, which results from rainfall in preceding years, is used in both the patch mosaic and the ecological criteria approaches to set targets for burning. Monthly thresholds with regard to progress towards these targets should be set (Fig. 2) to allow managers to continually assess the risk of drought, and to allow them to intervene (for example, by suppressing unplanned fires, or halting further ignition) if such risks are high.

Fire season

Targets can be set for the ratio of area burnt in late winter/early spring (August, September and October) to that burnt in late spring/summer (November, December and January). This ratio should be in the range of 2.25:1 to 1.75:1. This proportion is based on historic patterns of fire in the park (which were 2.25:1, Van Wilgen *et al. in press*), and allows for a shift towards later fires. The rationale behind this is that (i) the major proportion of the area burns in the dry season, when plants are dormant and adapted to survive fires, and (ii) that occasional early wet season or summer fires occur which, while detrimental to some species, will favour others through reduced competition after fire. The allowance for a proportion of fires to take place outside of the dry season is included to encourage a shift towards the late fires that would have made up part of a lightning-driven fire regime (Trollope 1993; Van Wilgen *et al. in press*).

Fire intensity

Most wildland fires would have burned under a range of intensities if they were ignited as point fires. They would have spread in all directions, thus burning as head, back and flank fires, and they would have burned both during the day (under hot, dry conditions) and at night (under cool, moist conditions), producing a range of intensities. Fire intensity plays a large role in the selective survival and recovery of species after a fire, and a range of intensities will therefore enhance co-existence of species and hence diversity. For each fire, the proportion that burns in low, moderate, and high intensity fires should be established. When the area burnt in any one of these classes is less than one quarter or more than half of the total area, then a TPC would have been reached. These thresholds are proposed to provide a range of intensities, which in turn should promote diversity. While it could be expected that headfires burning with the wind would always cover a larger proportion of any area burnt, the lowveld climate is not characterised by high windspeeds. This effect would therefore be limited, and 50% of the area could be seen as a reasonable threshold.

The extent of fires in any year

The extent of fires that can occur in any year is a function of grass biomass. Grass biomass is used to determine the extent of fire in two of the three proposed management approaches, and will in any case affect the area burnt if other approaches are followed. If the area burnt in any given year is small, concerns about deterioration of the grass sward in remaining unburnt areas (in terms of grazing value) may arise. On the other hand, if large areas burn in a single year, concerns around available habitat for certain species may arise. We suggest that thresholds be developed for different landscapes in the park, based on current grass biomass, to cater for the above concerns (Fig. 3). The management response will also be influenced if thresholds relating to long-term patterns of fire frequency are reached (Fig. 1). These may lead to alteration of annual targets in area burnt to adjust for long-term trends.

Fire size distribution

A distribution of fire sizes would be of interest to managers for a number of reasons. Too

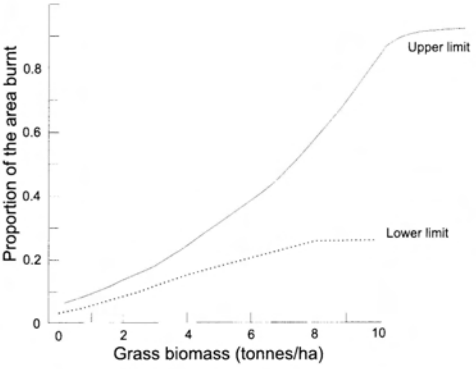

Fig. 3. Proposed thresholds of potential concern with regard to the area burnt within the current fire season, based on the amount of grass biomass at the beginning of the fire season (May).

many small fires could be of concern as herbivores would tend to concentrate on such areas, with possible detrimental effects. Very large fires, on the other hand, may impact on forage availability, even for highly mobile and wide-ranging animal species. Fire size distributions could be monitored against known patterns of distribution from past surveys, and any tendency towards extremes should trigger concern (Fig. 4).

The cause of fires

Although the cause of a fire has no ecological significance, it will be of concern if unplanned fires burn more than a certain percentage of the area burnt in all fires. It is suggested that this threshold be set at 25%. Exceeding this will indicate that managers are not achieving sufficient control over the fire regime to allow it to accomplish the desired effects (regardless of which approach is being followed).

Procedure to be followed

Under the different management approaches suggested for the Kruger National Park, many fires will not be confined to management blocks, but will be allowed to burn freely. Once any fire has burnt out, it's extent should be mapped at a scale of 1:50 000 and captured on a geographical information system (GIS), together with relevant information on the fire. The relevant information should include:

(i) the date(s) of the fire;

(ii) the cause, divided into lightning, prescribed burns (including firebreak burns), fires that enter the park from outside, escaped fires from burning operations, fires caused by unauthorised people (for example poachers or illegal immigrants), other known causes (to be specified), or fires of unknown cause;

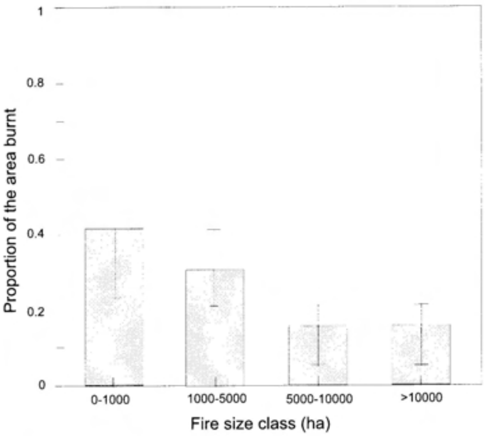

Fig 4. Thresholds of potential concern relating to the distribution of fires of different sizes over the 10 years prior to evaluation.

(iii) an estimate of the range of intensities of the fire (high, moderate or low), based on the efficiency of fuel consumption and tree scorch heights in the burnt areas (the estimates should state what proportion of the burnt area fell into each of these categories); and

(iv) an estimate of the percentage of the vegetation that remained unburnt within the area recorded. This estimate is needed to allow for the fact that many fires are very patchy, leaving "islands" of unburnt vegetation behind. If relatively large areas within a fire area did not burn, they should (as far as possible) be excluded from the area mapped as having burnt.

The GIS-based databases should be updated annually, by the end of February each year. At this stage, the long-term indices relating to fire frequency, seasonal distribution, the range of intensities, and the size distribution can be updated and examined to establish whether any thresholds of potential concern have been reached. If this is the case, then appropriate adjustments can be made to the annual burning targets to correct these trends. Once this has been done, all fires that occur as the year progresses should be mapped, and compared monthly to the thresholds relating to drought risk, extent of burn, and cause of fires. Again, if thresholds are reached, changes can be made to the annual targets for the year.

It is also important that data collected as part of other monitoring exercises be assessed against the background of a good database of fire occurrence. Monitoring data are notoriously unhelpful in showing the causes of recorded changes, and the fire records may help to address this problem by providing a causal backdrop. If thresholds are detected in any of these biological criteria (which includes information on veld condition, woody plant structure and composition, a range of animal populations, soils and erosion), then they should be related to the fire data in order to determine whether the threshold can be related to the occurrence and effects of fire.

Discussion

Appropriate goals for management

Management is goal-oriented, and in the past managers in the Kruger National Park have used fire to drive the system towards a desired stable state (Rogers 1997). With the more recent recognition that savanna systems are extremely dynamic and usually in a state of flux, goals need to change towards those that describe desired ranges of flux rather than fixed states. Fire, herbivory and cycles in rainfall are the major disturbances responsible for the dynamics of savannas; of these, fire and herbivory are the two that can be influenced by managers. Because of a history of stable-state thinking, ideas around "appropriate" fire regimes tended to descriptions of fixed return periods and seasons. The new goals of maintaining biodiversity "in all its facets and fluxes" will require fire management goals to be framed in terms of a range of return periods and seasons (where fire is being used as a surrogate measure for assessing the ultimate goal of biodiversity), or in a range of vegetation states (where fire is being used in an attempt to achieve such states). The former applies to the lightning and patch mosaic burning approaches, and the latter to the ecological criteria approach.

We have made some suggestions as to the descriptors of the fire regime that could serve as surrogate goals. Managers will have to agree on acceptable thresholds for these descriptors, and this process would have to be followed for each of the major landscapes of the park, as these differ significantly in their susceptibility and response to fire. The same applies if an approach based on ecological criteria is followed, except that the range of descriptors will have to be framed in terms of a distribution of vegetation structure and composition over space and time. We envisage that such distributions would provide for large proportions of certain types (for example grass swards dominated by decreaser grasses, and a representative distribution of size classes amongst tree species), but that there would be "tails" of smaller proportions of moribund, overgrazed, bush-encroached or treeless areas. Although these are undesirable in an agricultural sense, they could be acceptable in the interests of maintaining diversity in conservation areas.

While attempting to simulate natural processes, and allowing them to operate unchanged from historic conditions is obviously a primary goal of management in a National Park, there can, and should, be exceptions. Rare species (such as black rhino, roan antelope, or Pel's fishing owl, for example) could merit special intervention. Where these species' habitat requirements call for regular burning or protection from fire, and where their population levels call for special action to prevent local or even global extinction, then deviations from the general approach to fire management may be appropriate in some areas.

Dealing with uncertainty

The above attempt at predicting the outcomes of different fire management approaches (Table 1) has illustrated the difficulties in quantifying their outcomes in terms of the spatial and temporal patterns they will generate. Although each approach arises from a different philosophy (Table 1), they may, in reality, not differ in the physical fire patterns that they produce. The likelihood of this is increased by the fact that each approach will be affected to some degree by unplanned fires. Another source of uncertainty is that ecologists cannot accurately predict the biological consequences of these patterns on all elements of the biota. Despite the importance of fire in the dynamics of savanna ecosystems, demographic studies of savanna trees and grasses have been neglected (Bond & Van Wilgen 1996; Scholes 1997). In fact, for many years, ecologists working in savannas did not regard them as a separate biome—rather savannas were viewed as a special case of grassland or forest (Scholes & Walker 1993). Pasture scientists studied the grasses, and dealt with problems of "bush encroachment" (e.g. Trollope 1982); foresters dealt with tree species for timber production (e.g. Geldenhuys 1977). More recent studies have concentrated on determinants of savannas, such as water, herbivory and nutrients (see Scholes & Walker 1993, Solbrig *et al.*1996 for reviews). Despite the huge advances that have been made in understanding the determinants of savannas, therefore, we are poorly equipped to predict the impacts of fires, in combination with other factors, even on key plant and animal species. The recent recognition that savanna ecosystems cannot be managed to remain in a desired state, but rather tend to be in constant flux, further reduces the scope for predictive ecology.

If ecologists are to have an influence on the direction of conservation management, appropriate responses to the lack of predictive ability must be developed. It should be recognised that conservation management is goal-orientated, and managers seek to manipulate (either passively or actively) the forces that alter the nature of the landscape mosaic (e.g. Rogers 1997). In the case of fire management in the Kruger National Park, the goal is to conserve biodiversity through the application of an appropriate fire regime. Because of the difficulties inherent in predicting the effects of fire on all facets of biodiversity, we can use fire patterns as surrogate measures of biodiversity. For argument's sake, if we postulate that each of the three candidate systems will be able to conserve biodiversity equally well, this must be tested by monitoring both the fire patterns that establish themselves (the surrogate measures), and the responses of various plant and animal populations. Each of the biotic elements that are being monitored have their own TPCs, and should any of these thresholds be reached, then an assessment of the causes that led to such change will be prompted. Provided that fire patterns are also monitored, the changes can be interpreted against the background of a known fire history. This may lead to either a change in fire management approach, or the initiation of a research project to develop further understanding of the response (a "response research framework", Rogers 1997), or both. In the meantime, the fire patterns themselves form goals against which managers can assess progress towards the goal of conservation of diversity.

The future of fire research in the Kruger National Park

The change in approach to fire management offers the opportunity to review the research programme that was designed to support it. The original fire experiment (van der Schijff 1958) has not provided answers to the problems facing managers today. With hindsight, the experiment was flawed principally because the plots were too small to exclude impacts of artificially high levels of herbivory, and no allowance was made for variable fire frequencies. In view of the large proportion of research resources that would be needed to maintain the experiment, and the limited prospects for efficient and useful returns, it would seem sensible to terminate this experiment after an analysis of the data collected to date.

It has been accepted that the lightning fire approach should be implemented over the majority of the park, with the exception of smaller areas where the other two approaches will be implemented on an experimental basis. This would provide the focus for future fire research activities. The fire patterns that emerge, and the effects of these on the biota, should be monitored and used to identify priorities for experimental research. In addition, they should also underpin an active process of assessment and review of the approaches themselves. The outcomes should continually be assessed against TPCs, which may result in the abandonment of any of the approaches. The conditions that could lead to any approach being discontinued include:

(i) If it becomes clear that the outcomes, in terms of the fire patterns that establish themselves, cannot be separated from those produced by any other approach;

(ii) If any approach results in thresholds of concern being reached for populations of plant or animal species (especially rare species), which can be shown to be a result of fire; and

(iii) If any approach cannot be practically implemented, for example due to the costs involved, or because unscheduled fires become the dominant source of ignition.

The monitoring and interpretation of fire patterns, and decisions on the continuation or not of any approach, is a clear function of management. In the past, the curation and maintenance of fire records has been a research function of the Scientific Services branch within the park. While this may have been appropriate at the time, advances in computer technology have resulted in powerful tools being available to managers (Richardson *et al.* 1994). This fact, combined with the advantages associated with a sense of ownership and empowerment that accompanies the transfer of such a function, are strong arguments for the park's managers to assume the responsibility for monitoring and interpreting fire data. The research role can be to design monitoring systems (as described here), assist in the interpretation when TPCs are reached, and to initiate investigations where further understanding is required.

Conclusion

The thresholds of potential concern outlined in this paper are descriptive and preliminary. They are intended to illustrate the principle of using elements of the fire regime as surrogate measures and management goals, and will require refinement. This will both be necessary to make them applicable to the wide range of land types within the Kruger National Park, and to ensure their continual improvement. Reassessment and improvement are embodied in the concept of TPCs, and they will provide a focus for debate around changes and improvements to the management approaches with regard to fire. Managers in the Kruger National Park are able to build on one of the most comprehensive fire records for any ecosystem anywhere in the world (Van Wilgen *et al. in press*), and this provides a unique challenge of building appropriate management systems based on this excellent set of information.

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