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The ongoing development of a pragmatic and adaptive fire management policy in a large African savanna protected area

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ABSTRACT

This paper describes recent changes to the fire management policy of the 1.9 million ha Kruger National Park in South Africa. It provides a real-life example of adaptive learning in an environment where understanding is incomplete, but where management nonetheless has to proceed. The previous policy called for the application of fire to meet burnt area targets that were set for administrative subdivisions, and that were assessed at the scale of the entire park. This was problematic because the park is large and heterogeneous, and because sound ecological motivations that could link burning prescriptions to ecological objectives were missing. The new policy divides the park into five fire management zones on the basis of differences in mean annual rainfall, historic fire return periods, and geology. In addition, it proposes fire management actions designed to achieve specified ecological objectives in each zone, and includes fire-regime related thresholds and associated ecological outcomes against which to assess the effectiveness of management. The new policy is an improvement over previous iterations, but several challenges remain. Most important among these would be to continually improve the understanding of the effects of fire, and to develop frameworks for assessing the impacts of fire together with other ecosystem drivers that interact strongly with fire to influence the attainment of ecological objectives.

1. Introduction

Ecosystem management has to proceed in the face of changing environmental conditions and values, incomplete understanding of ecosystem processes and interactions, and of how management will affect these processes. A growing response to dealing with this complexity has been to implement adaptive management (Walters and Hilborn, 1976; Holling, 1978; Keith et al., 2011), where management goals are defined, alternative strategies are developed to achieve those goals, and outcomes are monitored and evaluated in terms of achieving the defined goals (Lindenmayer and Burgman, 2005). Adaptive management explicitly embraces uncertainty, recognising that management strategies may not deliver the desired results, that changes to these strategies may be required, and that understanding can be improved by experimenting with alternative approaches combined with monitoring, assessment and reflection (Biggs et al., 2011; Keith et al., 2011).

Vegetation fires shape the structure and composition of savannas, and fires are either applied or excluded to improve range condition and provide grazing for large herbivores, to promote tree growth, to conserve biodiversity, and, more recently, as a means to generate carbon credits (van Wilgen, 2009; Hassan et al., 2007; Russell-Smith et al., 2009). Early colonial experiments in savannas focussed on fire effects on trees, as the colonial governments placed a high value on tree cover (Laris and Wardell, 2006), but range scientists subsequently promoted burning to improve grazing (Tainton, 1999). Fire management provides substantial scope for the development of adaptive approaches to management and, in South Africa, adaptive ecosystem management has been pioneered in National Parks, notably the Kruger National Park (KNP, see Biggs and Rogers, 2003; Roux and Foxcroft, 2011; van Wilgen and Biggs, 2011).

The understanding of the ecological role of fire in savannas grew substantially in the late 20th century (Scholes and Walker, 1993; Andersen et al., 2005), which in turn led to changes in fire management in South Africa (Mentis and Bailey, 1990; van Wilgen, 2009). The switch from promoting grazing for large herbivores to conserving biodiversity in a broad sense left managers without a sound scientific basis to guide fire management (Bond and Archibald, 2003). Fire management, like other forms of ecosystem

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management, needs therefore to be continually adaptive to accommodate changes in understanding and shifts in management priorities. How well this is done, and whether it is effective in practice, is seldom reported in the scientific literature.

This paper describes recent changes to the fire management policy of the KNP. It provides a real-life example of the challenges faced by managers of fire-prone savanna ecosystems, and of how evolving ecological and other understanding has been used to formulate pragmatic approaches to fire management. The purpose of the paper is to document the rationale behind the changes, and to examine retrospectively whether the new policy would have affected past fire management decisions had it been in place over the past decade. It also examines the ecological basis for the management policies that have been adopted, and highlights remaining challenges.

2. The study area

2.1. Salient features of the Kruger National Park

The KNP (ca. 1,900,000 ha, elevation 260–839 m) is situated in north-eastern South Africa, sharing international borders with Mozambique to the east and Zimbabwe to the north. Mean annual rainfall varies from 750 mm in the south to 350 mm in the north (Fig. 1A), and variations about the mean can be marked from year to year. The western half of the KNP is underlain by relatively nutrient-poor granites, while the eastern half is predominantly underlain by relatively nutrient-rich basalt, but includes the Lebombo Hills (primarily rhyolite formations) running from north to south. The granite and basalt areas are separated by a relatively narrow shale band in the south (Fig. 1B). The KNP is traversed from west to east by the perennial Crocodile, Sabie, Sand, Olifants, Letaba, Levuvhu and Limpopo Rivers. There are four broad vegetation types in the KNP. These are savanna woodlands on granite, dominated by broadleaved trees in the genus *Combretum* in the southwest, relatively open grassy woodlands dominated by fine-leaved trees in the genus *Acacia* on basalt in the southeast, and woodlands dominated by mopane trees (*Colophospermum mopane*) on granites and basalts respectively in the northern parts of the KNP. The KNP supports a variety of large grazing and browsing mammal species, notably elephant (*Loxodonta africana*), white rhinoceros (*Ceratotherium simum*), hippopotamus (*Hippopotamus amphibious*), buffalo (*Syncerus caffer*), giraffe (*Giraffa*

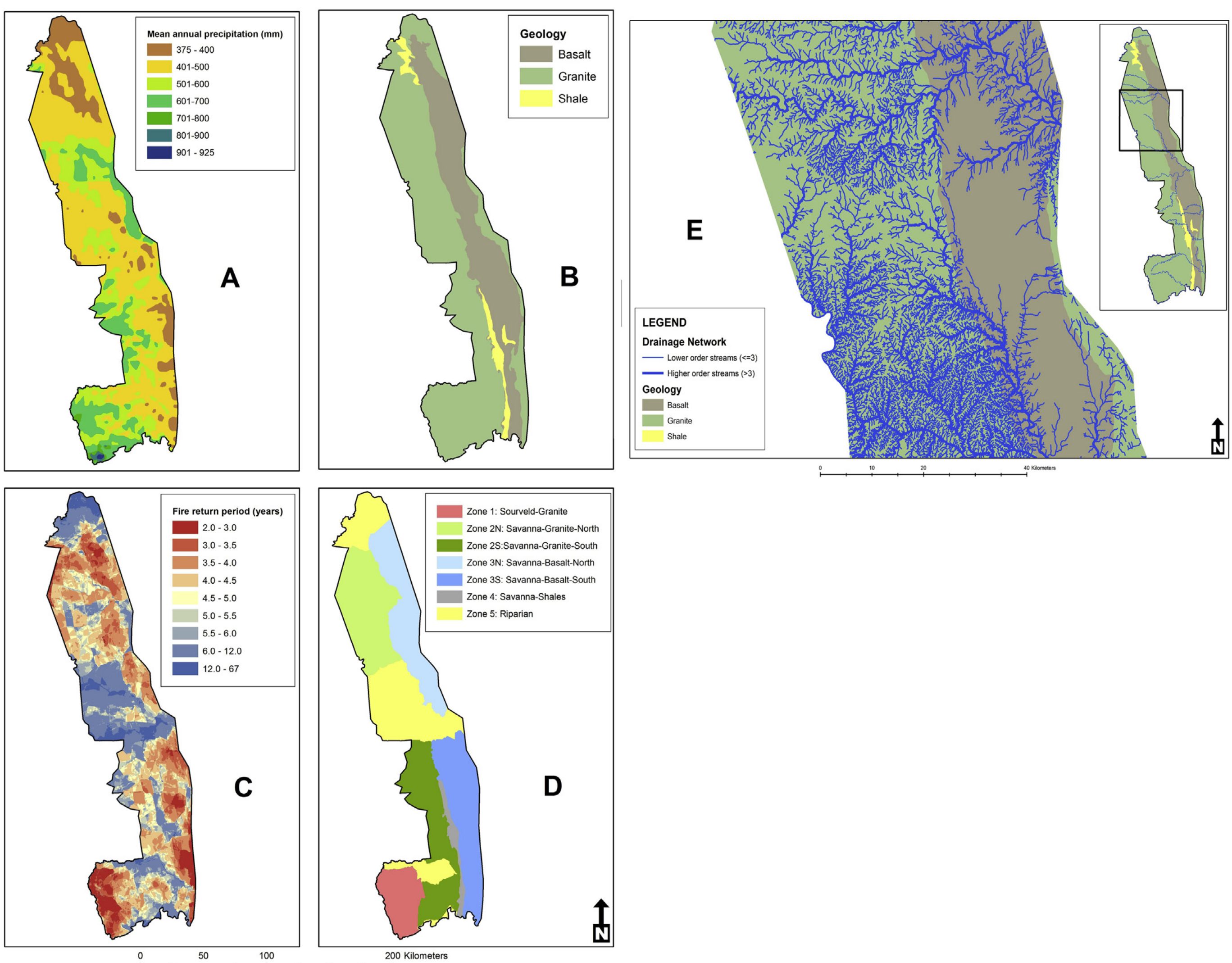

Fig. 1. Biophysical features used in the delineation of fire management zones in the Kruger National Park. A: Mean annual precipitation; B: The distribution of broad geological substrates; C: The distribution of mean fire return periods; D: Fire management zones; E: Drainage lines, included here to illustrate the marked differences in topographical heterogeneity between granite and basalt areas.

camelopardalis), zebra (*Equus burchelli*) and impala (*Aepyceros melampus*), and these play an important role (along with rainfall, fire and soil) in shaping the vegetation.

The fire regime (i.e. the combination of frequency, season and intensity of fires, Gill, 1975) in the KNP is characterised by moderate to high-intensity (Govender et al., 2006), late dry-season (July–October) fires at mean return intervals of 4.5 years (van Wilgen et al., 2000). The total area burnt per annum was found to be significantly correlated with rainfall cycles, and largely unrelated to the prevailing fire management policies (van Wilgen et al., 2004). The large-scale fire patterns within the KNP are strongly influenced by rainfall, geology and distance from the closest perennial river, and the interactions between these variables. Areas with higher rainfall, on basaltic substrates and far from rivers tend to burn more often, and have less heterogeneous fire regimes than areas with lower rainfall, on granitic substrates and closer to rivers (Smit et al., 2013).

The KNP is divided into 22 ranger sections, and section rangers are responsible for the implementation of all management activities, including burning and wildfire control in their section. Rangers typically have a tertiary qualification in environmental or conservation management, and/or the natural sciences. Rangers make significant inputs into policy and management debates through science-management fora, and they are expected to implement policy decisions taken at a higher level. In practice, they are allowed discretion with regard to prioritizing and implementing management actions, provided that the outcomes fall within the defined thresholds.

2.2. Fire science to inform management

The KNP has invested substantially over the past half century in the development of a scientific basis to underpin management (Du Toit et al., 2003; Joubert, 2007). In line with this philosophy, the KNP established an experiment in 1954 to investigate the effects of a series of fire treatments, and protection from fire, on range condition (van der Schijff, 1958). The experimental design is described in detail by Biggs et al. (2003). The findings of the experiment have been reported in 56 papers in the peer-reviewed literature to date (80% of which appeared after 1995), and the degree to which the experiment influenced changes in fire management policy was reviewed by van Wilgen et al. (2007).

2.3. The history of fire management in the Kruger National Park

The KNP has a long history of active fire management, which began in the mid-1950s when a policy of fire suppression was replaced by prescribed burning. Successive accounts of the history of fire management in the KNP are provided by Brynard (1972); Braack (1997); Biggs and Potgieter (1999); van Wilgen et al. (2003); Joubert (2007); and van Wilgen et al. (2008). The first active fire management policy in the KNP was introduced in 1957, and called for regular burning in spring (October, after the first rains) on fixed areas (burning blocks) on a three-year cycle. This policy, with adjustments that allowed more variation from 1981, remained in place for 35 years before it was replaced in 1992 by a policy that sought to restrict fires to those caused by lightning only. In 1998, following a detailed analysis of historic fire regimes in the KNP, a set of thresholds was formulated. These thresholds defined the bounds of fire regime in terms of season, frequency, intensity, size distribution and cause. If the thresholds are exceeded, it would trigger a management response (van Wilgen et al., 1998). The thresholds describing fire patterns over the period when the lightning fire policy was in place were not exceeded, except in the case of fire cause. With respect to fire cause, it became apparent that a regime dominated by lightning ignitions was not being achieved, and that the majority of fires were of human origin. This led to further policy changes, and the introduction in 2001 of a system intended to achieve annual burnt-area targets through the application of point-ignition patch burns throughout the fire season. The success of the 2001 policy was to be assessed in terms of the achievement of heterogeneous spatial distribution of fire patterns, and a range of fire intensities. Although the targets were determined separately for the KNP's 22 ranger sections (designated as 'large fire management units', LFMUs), the spatial distribution and intensity pattern thresholds associated with these targets were assessed at the level of the entire KNP.

The 2001 fire policy included the following steps:

I. Division of the KNP into 22 LFMUs;
II. At the start of each fire season, a percentage of the LFMUs to be burnt in the coming season was estimated based on rainfall over the preceding two years (van Wilgen et al., 2004; Archibald et al., 2010b);
III. Division of this annual percentage into monthly burnt area targets;
IV. Application of point-ignition fires to achieve monthly burnt area targets, taking into account unplanned fires, and allowing lightning-ignited fires to develop later in the season; and
V. An annual assessment of realised against desired patterns of fire intensity and fire heterogeneity (the spatial pattern of burnt and unburnt areas, see van Wilgen et al., 2004). A fire intensity threshold would be reached if the area covered by fires in any of three intensity classes (low, moderate, and high) constituted $<20\%$ or $>50\%$ of total area burnt in the KNP in a given year.

2.4. Problems and the need for change

The 2001 fire policy sought to encourage a range of spatial patterns and fire intensities, in the interests of encouraging variability. Fires were classified as being of low, moderate or high intensity (based on the estimated fuel loads and the season of burn, van Wilgen et al., 2008), and thresholds for area burnt in each category were set to promote a range of fire intensities. An assessment of fire patterns following 5 years of the application of this policy (2002–2006) revealed no cause for concern regarding fire scar spatial heterogeneity, but found that fire intensity thresholds had been exceeded. Fires in the high intensity category constituted more than the threshold of 50% of the area, and accounted for 70–80% of the area burnt in some years (van Wilgen et al., 2008).

Using the estimated intensity of fires as a basis for assessing whether fire regimes are within acceptable boundaries is, however, problematic for several reasons. Fire intensity is not included in fire records, and has to be estimated by making a number of assumptions about the fuel loads and the environmental conditions under which they burnt (van Wilgen et al., 2008), which could lead to inaccuracies. These inaccuracies are compounded because only one intensity value is assigned to each fire, ignoring potentially large variations in intensity within each fire. In addition, the assumption is being made that variability in fire intensity would have desirable effects on the ecosystem, without any strong ecological evidence to support the choice of thresholds. The lack of an ecological basis for the formulation of thresholds has long been recognised. As was pointed out in the original paper that proposed these thresholds (van Wilgen et al., 1998), and critiqued elsewhere (Parr and Andersen, 2006), there is a need for ecological studies to assess the impacts of fire regimes. The inclusion of the thresholds that address the ecological outcomes of fire regimes, rather than the fire regimes themselves, is overdue. A refinement of the thresholds from one measure for the entire KNP was also obviously necessary to cater for significant differences (in mean annual rainfall, inter-annual rainfall variability, geology and soils) between the different parts of the KNP (Smit et al., 2013). Until 2012, separate targets for area to burn were created annually for the 22 LFMUs, but the assessment of realised patterns against thresholds was done for the whole KNP, which was unsatisfactory. The use of ranger sections to define the 22 LFMUs had no ecological basis, and a subdivision based on biophysical and ecological criteria, and not on administrative boundaries, was also necessary.

3. Development of revised management policy

3.1. Delineation of fire management units

The delineation of a new set of LFMUs was informed by historic fire return periods, geological substrate and mean annual rainfall (Smit et al., 2013). Fire return periods were estimated from fire scars that have been mapped in the KNP since 1941. The techniques employed have evolved from hand-drawn maps to satellite-derived fire-scar delineation, increasing in accuracy as technology advanced (van Wilgen et al., 2000; Archibald et al., 2010a; Govender et al., 2012). The older maps were captured in spatial format and stored in a Geographical Information System (GIS), resulting in a continuous fire scar history since 1941 for the KNP. An analysis of the GIS database revealed distinct areas in which fires were more, or less, frequent (Fig. 1C), with return periods ranging from about 2 years to >10 years, as well as areas that have never burnt. This map was used to derive a first sub-division by separating the areas subjected to frequent burning (every 2–4 years) from those subjected to less frequent burning (every 5–10 years). Although these mean fire return periods reflect the joint outcome of successive fire policies, the individual means for different fire policies are unlikely to have differed, as the fire return periods were more strongly influenced by the sequencing of annual rainfall than by management (van Wilgen et al., 2004).

The underlying geology was then used to separate LFMUs on granite, basalt and shale substrates (Fig. 1B), and rainfall isohyets (Fig. 1A) were used to separate the more mesic southwest from areas of lower mean annual rainfall.

This delineation revealed five distinct zones, which were divided into 10 LFMUs (Fig. 1D):

I. Zone 1 (one LFMU): High rainfall areas on relatively nutrient-poor granite ('sourveld'), subject to frequent burning;
II. Zone 2 (two LFMUs): Savannas on granite, subject to a moderate burning frequency. This zone was spatially separated by zone 5, and was subdivided into two LFMUs, designated as zones 2 south and north respectively;
III. Zone 3 (two LFMUs): Savannas on basalt, historically subjected to frequent burning. This zone was also spatially separated by zone 5, and similarly divided into zones 3 south and north respectively;
IV. Zone 4 (one LFMU): A distinct area characterised by infrequent fire, occurring on shales; and
V. Zone 5 (four LFMUs): Areas associated with major river systems, characterised by very infrequent fires, and separated into four LFMUs along the major rivers and their tributaries.

With the exception of zone 4 (where an abrupt geological boundary is reflected by a corresponding and easily discernible vegetation boundary), the final boundaries of LFMUs were moved to the perennial rivers and/or roads closest to the ecological (geology, rainfall or fire frequency) boundary, to make the boundaries tangible. In addition, roads and rivers could act as firebreaks between units with differing fire management objectives.

3.2. Formulation of ecological management objectives

3.2.1. Agreement on objectives and management actions

Many ecological management objectives are influenced by fire. The most important of these were identified in workshops that included KNP scientists and section rangers responsible for fire management. In addition, fire-related management actions that would be required to achieve the ecological objectives were agreed upon (Table 1). The rationale for the selection of the objectives and management actions is provided for each zone in Sections 3.2.2–3.2.6.

3.2.2. Zone 1. Sourveld on granite

This is a zone of relatively high rainfall which burns frequently (fire return periods of between 2 and 4 years). Granite-derived soils support a grass sward that is relatively low in nutrients, and relatively high rainfall drives high biomass production that leads to a build-up of fuels and a decline in palatability in the absence of frequent fire ('sourveld'). Regular burning is regarded as desirable for maintaining the forage value of the grass sward (Trollope et al., 2014). The zone is also prone to encroachment by woody vegetation ("bush encroachment"), which is driven by a number of interacting factors, the most important of which could be increases in grazing pressure, decreases in fire frequency and intensity, and elevated levels of atmospheric CO_2 (Buitenwerf et al., 2012). Bush encroachment can in turn be countered by the use of high-intensity fires (Trollope, 1974; Smit et al., 2010). There is also a concern that fuel loads that accumulate in the absence of burning could increase the risk of unplanned wildfires to infrastructure, animals and human life.

Workshop participants agreed that regular prescribed burning would be needed, and should be conducted over a variable area estimated each year from rainfall over the preceding seasons (van Wilgen et al., 2004; Archibald et al., 2010b). The inclusion of high-intensity fires should be considered in areas where a reduction of encroachment by woody vegetation is deemed necessary.

3.2.3. Zone 2. Savanna on granite

This zone is characterised by fires of moderate frequency (fire return periods of between 3 and 6 years). The zone has a relatively complex topography, characterised by granite outcrops and numerous drainage lines (Venter et al., 2003, Fig. 1E), which presumably results in a wide variety of realised fire behaviour in any given fire, although fire data at this scale are not available. These characteristics are thought to provide sufficient refugia for some tall trees to escape high-intensity fires, and opportunities for tree saplings to be recruited into larger, fire-resistant size classes, although there are no actual data to substantiate this belief. There are also concerns that encroachment by woody plants would occur (Eckhardt et al., 2000), and these can be countered through the use of an appropriate proportion of high-intensity prescribed burns. In addition, large, uncontrolled wildfires could present management problems, and the risk of such fires occurring could be reduced through judicious patch burning early in the fire season.

Although an annual predicted area for burning will be estimated, it would be acceptable for a smaller, or greater, area to burn, and the amount of burning is left to the discretion of the relevant section ranger. The inclusion of high-intensity fires in areas where a reduction of encroachment by woody vegetation is desired could also be considered. In addition, low intensity fires earlier in the fire season could be strategically placed to create mosaic of fuel breaks, at the discretion of the section rangers concerned.

Table 1
The ecological objectives of fire management, and proposed fire management actions to achieve those objectives, in large fire management units (LFMUs, which are zones or subdivisions of zones) in the Kruger National Park. See Fig. 1D for the distribution of zones and LFMUs. The rationale for the management actions is provided in the text. Thresholds against which the outcome of fire management will be assessed are in Table 2.

Zone	Ecological management objectives	Fire-related management actions
Zone 1. Sourveld on granite.	Improve the grazing quality of grass layers Halt or reverse trends of encroachment by woody vegetation Reduce the risk of large, high-intensity wildfires	Regular prescribed burning to approximate the predicted burnt area estimated from preceding rainfall over the past two years Inclusion of high-intensity fires in areas where a reduction of encroachment by woody vegetation is desired. Strategic placement of early season, low intensity fires to create a mosaic of fuel breaks, for example along the crests of hills.
Zone 2. Savanna on granite. Divided into two LFMUs, North and South	Halt or reverse trends of encroachment by woody vegetation Reduce the risk of large, high-intensity wildfires	Prescribed burning as and where deemed necessary by the section ranger concerned. Inclusion of high-intensity fires in areas where a reduction of encroachment by woody vegetation is desired. Strategic placement of early season, low intensity fires to create a mosaic of fuel breaks, for example along the crests of hills
Zone 3. Savanna on basalt. Divided into two LFMUs, North and South	Improve herbaceous quality and heterogeneity, and encourage seasonal attraction of grazing herbivores Prevent further loss of large trees Encourage recruitment of tree saplings into life stages where crowns are not subject to lethal scorching by fires	Prescribed burning limited to an area of less than 50% of the predicted burnt area estimated from rainfall over the past two years Reduce the risk of unplanned fires entering the KNP from Mozambique by maintaining an adequate firebreak along the eastern border Strategic placement of early season, low intensity fires to create mosaic of fuel breaks
Zone 4. Savanna on shale formations	Maintenance as a natural firebreak between zones 1 and 2 in the south.	Deliberate prescribed burning to be limited to rare occasions when reduction of fuel if deemed necessary for safety purposes for infrastructure protection. Tolerance of unplanned wildfires.
Zone 5. Areas adjacent to riparian zones. Divided into 4 LFMUs along major river systems	No specific fire-related objectives.	Tolerance of unplanned wildfires Deliberate prescribed burning to be limited to rare occasions when reduction of fuel is deemed necessary for safety purposes Fuel-reduction burns around important infrastructure, where necessary.

3.2.4. *Zone 3. Savanna on basalt*

This zone is currently characterised by frequent to moderately frequent fires, at return intervals between 2 and 5 years. Experienced section rangers were of the opinion that the LFMU in the south attracted large numbers of grazing herbivores in winter in the past, but that this phenomenon has become less marked in recent years, possibly in response to declines in range condition brought about by frequent burning (Trollope et al., 2014), as many fires enter the KNP from the east in Mozambique. Fires are also thought to be excessively intense, as indicated by recent assessments (van Wilgen et al., 2008). In addition, this landscape may have experienced structural homogenization of the vegetation, especially through the loss of the tall tree component (Eckhardt et al., 2000), possibly because of frequent and high intensity fires. Finally, in this landscape, encroachment by woody shrubs is less of a concern than on the granite areas (Eckhardt et al., 2000).

Because the basalt areas are topographically less diverse than the granite areas (Fig. 1E), fire behaviour tends to be less variable on basalts. Large, frequent, high-intensity fires dominate, and promote grasses such as *Themeda triandra* and *Bothriochloa radicans*, which are relatively unattractive to grazers, leading to a build-up of fuel and more intense fires. Because grazers target recently-burnt areas, it is hoped that a reduction in burning could lead to focussed rather than widespread grazing, and could result in increased heterogeneity in the grass sward (see, for example, Archibald et al., 2005). This heterogeneity (in fuel structure) would in turn promote heterogeneity in fire behaviour. It is also hoped that this will provide more opportunities for tree saplings to be recruited into larger, fire-resistant size classes.

In this zone, the management imperative would therefore be to reduce both the frequency and intensity of fires. The risk of unplanned fires entering the KNP from Mozambique should be reduced by employing new technology to maintain an adequate firebreak along the eastern border (Austen et al., 2011). Low intensity fires should be set at the start of the burning season to create a mosaic of fuel breaks, which would in turn further reduce the risk of large, unplanned fires in the later dry winter months. By burning a smaller area each year, it is also hoped that the trend towards homogenization of the grass sward will be reversed.

3.2.5. *Zone 4. Savanna on shales*

This zone is characterised by infrequent fires. It rarely burns due to the high levels of herbivory of palatable grasses, and dominance by dense woody vegetation. The zone is elongated and narrow (Fig. 1D) and forms a natural firebreak (due to low herbaceous fuel loads) between the southern LFMUs on granite and basalt respectively. It will in future be managed as a convenient firebreak between these two LFMUs, where the goals of, and approaches to, fire management differ. Workshop participants agreed that no fire targets need to be set for this LFMU, and deliberate burning should be limited to rare occasions when reduction of fuel may be deemed necessary for safety purposes around infrastructure.

3.2.6. *Zone 5. Areas adjacent to major rivers*

Fire rarely occurs in this zone, for a range of possible reasons (Smit et al., 2013). These are thought to include higher grazing pressure from herbivores that are water-dependent, thus reducing fuels; a smaller ignition catchment, as fires that originate on one side of a river rarely cross to the other side; the presence of more tributaries closer to larger rivers, which would further impede the spread of fires; and a topographic affect brought about by the fact that fires spread faster uphill than they do downhill, and rivers are always at the lower elevation. It is therefore proposed that no deliberate burning should be conducted in these LFMUs, but that unplanned wildfires that may occur should simply be tolerated. Deliberate burning would be limited to rare occasions when reduction of fuel would be deemed necessary for safety purposes to protect infrastructure.

Table 2
Fire-related thresholds, and associated ecosystem-related outcomes, that will be used to assess whether or not the objectives of fire management are being achieved in five fire management zones in the Kruger National Park.

Zone	Fire regime-related thresholds	Associated ecological outcomes
Zone 1. Sourveld on granite	Fires should burn at least an area equal to the area that would be expected to burn as estimated from the previous two year's rainfall. Fires should burn an at least 33% of the LFMU measured as a moving average over the past 5 years. At least 10% of area of the area that would normally burn (as determined by previous two year's rainfall) should burn in high intensity fires	Maintenance of acceptable quality of grazing and composition of the grass sward Reductions in the cover of woody vegetation
Zone 2. Savanna on granite.	None	Reductions in the cover of woody vegetation
Zone 3. Savanna on basalt.	No more than 50% of the predicted area that would normally burn (based on previous two year's rainfall) should burn in any given year. No more than 10% of the area that would normally burn (as estimated from the previous two year's rainfall) should be in high intensity fires	Maintenance of acceptable quality of grazing and composition of the grass sward Halt, retard or reverse the loss of large trees
Zone 4. Savanna on shale	Management fires to promote safety and protect infrastructure should not exceed 10% of the area in any year	None
Zone 5. Areas adjacent to riparian zones.	Management fires to promote safety and protect infrastructure should not exceed 10% of the area in any year	None

3.3. *Formulation of thresholds*

3.3.1. *Fire and ecosystem thresholds*

Fire management in the KNP is adaptive, in line with approaches to the management of other ecological processes (van Wilgen and Biggs, 2011; Roux and Foxcroft, 2011). Adaptive management involves the formulation of targets, and then of thresholds, with the help of experts, to describe the boundaries of the desired state that management aims to maintain (in line with the objectives set out in Table 1). Once management actions to maintain the system within the agreed thresholds have been identified and accepted, they are implemented, and the outcomes are compared to thresholds. In cases where thresholds are exceeded, consideration is given to management interventions that could drive the system back to within thresholds, or, alternatively, thresholds can be re-calibrated.

To date, fire management thresholds have been expressed in terms of fire patterns, and not ecological outcomes (van Wilgen et al., 2011). Fire-related thresholds were based on the untested assumption that a diverse fire regime would promote biodiversity, but a better understanding of the links between fire, other driving factors, and biological outcomes would be needed for progress to be made in defining more meaningful thresholds. The revised policy described here is a step in that direction, in that, while it still proposes that fire patterns be monitored, these are now explicitly linked to ecological objectives (Table 1). The fire-related thresholds that will be used to assess whether objectives are being achieved are presented and quantified (Table 2), and the outcomes of past fires are examined in terms of these thresholds for each of the LFMUs (Section 4). In addition, we propose ecological outcomes that could be used to formulate ecological thresholds that would be specifically linked to fire patterns (Table 2). These ecosystem-related thresholds are not quantified here, as they are to be catered for elsewhere (e.g. Grant et al., 2011; McGeoch et al., 2011), but it would be necessary to consider the cause-and-effect relationships between fire and ecological thresholds when assessing the outcomes of management, something that has not explicitly been done to date. The proposed fire thresholds, and associated ecosystem-related outcomes are outlined in Sections 3.3.2–3.3.5.

3.3.2. *Thresholds for sourveld on granite*

Fire-related thresholds: Management will seek to encourage frequent burning in this zone, so a threshold of the full predicted area that would be expected to burn each year (as determined from preceding two year's rainfall and/or from grass fuel loads) has been set. A target of burning at least 33% of the area over a five-year moving average, constitutes a second threshold. Setting the lower threshold equal to the full predicted area could lead to overburning (i.e. exceeding the predicted area in a given year would be tolerated, but failing to reach in another year it would trigger additional burning, leading in the long term to more burning than has been experienced in the past). However, data from the KNP fire experiment suggest that sourveld areas can be burnt frequently (annually) without detrimental effects (van Wilgen et al., 2007; Smith et al., 2013). In addition, a proportion of these fires should be of high intensity, to reverse bush encroachment. To ensure this, a threshold of at least 10% of the area of all fires burnt in high and very high intensity fires is proposed, subject to all safety requirements being met.

Ecosystem-related outcomes: Fire affects the composition and quality of the grass sward, and the proportion of woody vegetation. Thresholds to monitor these outcomes should be set in terms of the composition and quality of the grass sward, and the cover of woody vegetation.

3.3.3. *Thresholds for savanna on granite*

Fire-related thresholds: In this zone, it is assumed that the heterogeneous topography would result in equally heterogeneous fire patterns and intensities (see Section 3.2.3), and that monitoring of these patterns would not be necessary. Consequently, no fire-related thresholds are proposed for this zone.

Ecosystem-related outcomes: Fire affects the proportion of woody vegetation in this zone, and thresholds to monitor outcomes should be set in terms of the cover of woody vegetation. In particular, insufficient fire may exacerbate bush encroachment.

3.3.4. *Thresholds for savanna on basalt*

Fire-related thresholds: In this zone, there is a concern that fires are too frequent and too intense (Section 3.2.4). Management should therefore aim to reduce the frequency of fires, and a threshold has been set that no more than 50% of the predicted area (as estimated from preceding two year's rainfall and/or from grass fuel loads), should burn in any given year. Keeping the area burnt at half of the predicted area (i.e. the area that would normally be expected to burn) may not be sustainable in the long term. However, the threshold is based on historic burning that included both deliberate ignitions (which will now be reduced) and many wildfires that originated outside of the KNP, and where determined attempts are expected to reduce their occurrence (e.g. by improving boundary firebreaks, Austen et al., 2011). Should the goal of reducing fire frequency prove to be unattainable, the threshold may have to be revised. In addition, there is a desire to reduce fire intensity, and the relevant threshold is that no more than 10% of the predicted area should be in high intensity fires.

Ecosystem-related outcomes: The management concerns expressed here relate to the quality of grazing, and the ongoing loss of large trees. Thresholds to monitor these outcomes should be formulated in terms of the quality and composition of the grass sward, and the density of tall and emerging tall trees.

3.3.5. Thresholds for shale and riparian areas

The use of fire would not be required in the ecosystems of zones 4 and 5, which rarely burn, and the philosophy would be to treat them as "wilderness" areas, where management interference is kept to a minimum. The only concern here would be if management fires, carried out for reasons of safety rather than ecosystem health, were to constitute an unacceptably large proportion of the area burnt. A threshold of no more than 10% of the area burning in management fires has been set.

4. Retrospective assessment of outcomes

4.1. Methods used

The fire management thresholds described above were formally adopted for implementation in February 2012. We assessed fire patterns that were associated with the preceding 2001 fire policy, to retrospectively assess the degree to which these patterns would have exceeded the thresholds (Table 2). Fire scars were mapped annually using MODIS (FIRMS, 2011), which detects fires of >6.25 ha, an appropriate resolution for supporting management assessments at the scale of the KNP. A change detection model was applied to monthly pre- and post-fire images in ArcMap 10, Model Builder (ESRI, 2010) using MODIS near infrared band 2 (841 nm–876 nm). The resulting raster was classified into five classes using natural breaks. Zones of greatest change were classified as burnt and verified on the ground with Global Positioning System coordinates obtained from section rangers for all fires, as well as from active fire coordinates from the Advanced Fire Information System (AFIS) (AFIS, 2011). AFIS uses MODIS to detect fires at approximately six-hourly intervals at a 1-ha scale.

The area y (in 1000 s of ha) that would burn in any given year was estimated as $y = 1296.6\,x - 393\,031$ (van Wilgen et al., 2004), where x is the mean annual rainfall in each LFMU over the past two years. As output y provides an estimate for the whole KNP, the burnt area for each LFMU was estimated as $b\,(y/a)$, where $a =$ the area of the KNP, and $b =$ the area of each LFMU.

Each fire was also classified as low, moderate or high intensity, using relationships between biomass and fire season, and adjusted for weather on the day of the fire using the Angström Fire Danger Index (van Wilgen et al., 2008). Inputs for calculating the Angström Fire Danger Index include relative humidity and air temperature, which were obtained from the closest automatic weather station to the fire. Grass biomass was estimated as $z = 382.9 + 3.3\,x + 979.4\,y - 0.001\,x^2 + 0.37\,xy - 161.8\,y^2$, where $z =$ fuel load (kg ha^{-1}); $y =$ time since the last fire (yrs); and $x =$ mean rainfall over the past two years (mm) (Govender et al., 2006). Mean annual rainfall was estimated from weather stations within each LFMU. Each fire was assigned to one of the approximately 400 burning blocks (mean size ~ 4100 ha) that formed the basis of prescribed burning between 1957 and 1981. Blocks were assumed to have burnt if the entire block, or part of the block had burnt, to enable the estimation of fire return periods from fire records that overlapped precisely (MODIS images were only available from 2004; the assumption that the entire block had burnt would lead to an overestimate of fire frequency and a corresponding underestimate of fuel load and thus fire intensity). Fire return periods >6 years were assumed to be 6 years (only ~8% of the area burns in vegetation with a post-fire are >6 years, and grass biomass remains fairly constant once this age is reached; see van Wilgen et al., 2004; Govender et al., 2006).

4.2. Retrospective assessment of fire patterns

Fires in zone 1 (sourveld on granite) burnt an average of 36% of the zone each year between 2002 and 2012. The threshold for area to burn (at least the full predicted area, based on the previous two year's rainfall) was reached in all years except 2006 and 2011, when smaller areas than this threshold were burnt. The proposed goal of ensuring that a running mean of at least 33% burnt over 5 years was only marginally not attained in 2 years, when the running means were 32 and 28% respectively. The fire intensity threshold (that at least 10% of area of the predicted area to burn should burn in high intensity fires) was not reached in only one of the 11 years examined (2012). The picture that emerges for zone 1, therefore, is that the goal of promoting frequent fire and a reasonably high proportion of high-intensity fires was achieved over the past decade.

Fires in zone 2 (savanna on granite) burnt an average of 15% of the zone each year between 2002 and 2012, compared to an average predicted area of 12% per year. It seems therefore that, on average, the actual area burnt was higher than would have been expected from established relationships between rainfall, fuel production, and area burnt. This situation probably arose because of a high incidence of unplanned fires rather than because of excessive deliberate burning. As there are no fire-related thresholds in this zone, there would have been no reason to adjust fire management had the policy described here been in place since 2001.

About 22% of zone 3 (savanna on basalt) burnt every year, on average, between 2002 and 2012, against an average annual predicted area of 11%. The threshold for area to burn (that no more than 50% of the predicted area should burn in any given year) was exceeded in all years except 2012 in zone 3 north, and 2003, 2007 and 2012 in zone 3 south. The threshold for fire intensity (that no more than 10% of area predicted to burn should be in high intensity fires) was exceeded once in both zone 3 south, and zone 3 north in 2011. It would appear therefore that fires in this zone could be regarded as too frequent but not too intense. Under the new fire policy, had it been in place since 2001, attempts would certainly have been made to reduce the number of fires over the past decade.

Only 9 and 8% of zone 4 (savanna on shale), and zone 5 (areas adjacent to rivers) burnt on average between 2002 and 2012 respectively. These zones should not be burnt other than for safety reasons, and the only fire-related threshold is that management fires to promote safety should not exceed 10% of the area in any given year. However, because the cause of fires has not been consistently recorded, the threshold could not be assessed in those years when the total burnt area exceeded 10% (i.e. Zone 4: 2002; 2005; 2010 and Zone 5: 2002; 2004 and 2006).

5. Discussion

5.1. The role of research in informing the development of management policy

The objective of ecological fire management, as stated in the KNP's objectives hierarchy, is to 'understand the role of fire as a natural process (and other important interacting co-drivers) in the KNP and its ecosystems to develop an informed context for management' (van Wilgen and Biggs, 2011). Against this background, and taking cognisance of the fact that understanding is incomplete but that management must continue despite this, the KNP approach has been to implement burning policies and to monitor and interpret the outcomes, through ongoing research, monitoring and evaluation, within a framework of learning and continuous improvement. Initiated in the late 1990s, it is the only example of which we are aware of the implementation of adaptive fire management over a large area. It has led to several modifications in fire management over the past 15 years (Biggs and Potgieter, 1999; van Wilgen et al., 2008; van Wilgen and Biggs, 2011). Both the KNP fire experiment, and studies at a broader scale, informed these modifications. The KNP fire experiment revealed: (1) that species diversity was maintained by frequent (even annual) burning in high-rainfall (sourveld) areas (O'Regan, 2005; Smith et al., 2013; Trollope et al., 2014); (2) that frequent burning resulted in declines in range condition at more arid sites (Trollope et al., 2014); (3) that decreases in woody vegetation cover could be brought about by more frequent burning (Smit et al., 2010); and (4) that the total exclusion of fire increased woody plant density and biomass substantially (Higgins et al., 2007). Although results from the fire experiment did not directly trigger important changes to fire management policy in the past, the experiment supported adaptive management by contributing to predictive understanding (van Wilgen et al., 2007). This understanding was combined with other research at a landscape scale to inform policy changes. These landscape-scale studies indicated, for example, that too many high-intensity fires would impact negatively on large trees (high-intensity fires retard the recruitment of tree saplings into taller, fire-resistant age classes, Higgins et al., 2000, and may increase the rate of collapse of elephant-damaged trees, see Section 5.2); and that manager's ability to influence fire return periods was limited over large areas, although they could influence the spatial and seasonal distribution of fires (van Wilgen et al., 2004). Despite these advances in understanding, several important questions still require answers, as outlined in the sections below.

5.2. Management inputs and ecological outcomes

Two questions need to be considered when designing fire policies that seek to achieve ecological goals. The first is whether, and to what degree, fire management can determine or influence the long-term fire regime that manifests itself in a particular area. The second is how, and to what degree, the manifested fire regime influences the desired ecological outcome. A decade ago it was already recognised that management had little effect on total area burnt (as this was more strongly influenced by rainfall-driven grass production, although management did influence the spatial distribution of fires (van Wilgen et al., 2004). More recent research has focussed on additional factors that interact strongly with fire, or even over-ride the effects of fire, on ecological outcomes. For example, there is evidence that rising levels of atmospheric CO_2 may be driving bush encroachment in the KNP despite regular burning (Buitenwerf et al., 2012). The interactions between fire, elephants and tree mortality in the KNP have also been assessed in at least three recent studies (Vanak et al., 2012; Shannon et al., 2011; Helm et al., 2011). While conventional understanding suggests that savanna fires alone do not affect large trees, the combination of elephant damage and fire does lead to increased tree mortality. Elephants do substantial damage to trees, by breaking branches and stripping bark, which exposes bare wood to insect damage and further weakening in successive fires, ultimately resulting in the collapse of trees. Vanak et al. (2012) showed that 11.4% of >2500 sampled trees (>5 m) had died over two years. Elephant damage was the main predictor of this mortality, because of the link between exposure of dead wood through elephant damage and subsequent further damage in fires. The level of mortality of large (>5 m) trees was estimated as twice the recruitment rate from trees in smaller size classes (Shannon et al. 2011). Elephant numbers have more than doubled since culling ceased in the 1990s, and the widespread provision of permanent water also allowed for population increases; declines in large trees can therefore be expected to continue. The combination of a "fire trap" (where high-intensity fires reduce the rate of recruitment of tree saplings into taller, fire resistant classes) and an "elephant trap" (where elephants kill large trees, directly or indirectly) can lead to continued loss of large trees from the landscape (Anser and Levick, 2012). All of these studies confirm that the role of fire in driving declines in large trees cannot be considered in isolation.

The influence of management interventions (prescribed burning, firebreak establishment, and fire suppression or containment) on longer-term fire regimes (which is what ultimately matters) is difficult to predict, largely because many unplanned fires, over which there is less control, occur (Fig. 2). Further, fires combine with other factors, some of which also cannot be controlled, and it is the combination of these factors that determines the outcomes that managers seek to promote (Fig. 2). Although the links between the prevailing fire regimes and ecosystem features (notably on key areas of concern such as bush encroachment, the decline in numbers of large trees, and in range condition) are increasingly better understood, the question of how to effectively influence desired outcomes remains challenging, both because of limited understanding, and an inability to control some of the key drivers.

5.3. Implementing iterative improvement

Given the incomplete state of understanding, and the inability of managers to control some of the important determinants of outcomes, the question of whether the policy changes described here are a 'step in the right direction' arises. Our retrospective examination of fire patterns over the past decade suggests that management may well have acted differently had they been guided by the revised thresholds outlined here. Equally importantly, in zones 4 and 5, there would have been no imperative to

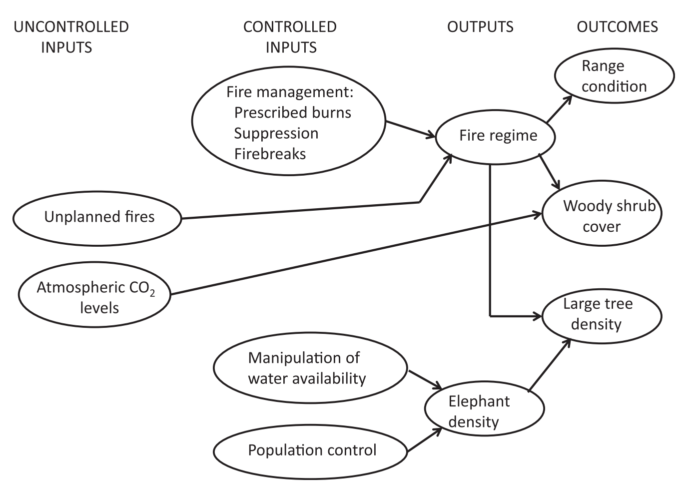

Fig. 2. Simplified conceptual diagram showing the relationships between ecosystem drivers (inputs) over which there is little or no control, management (controlled) inputs, outputs in terms of fire regimes and elephant numbers, and ecological outcomes (woody shrub cover, large tree density and range condition) that constitute the ultimate goals of management.

burn at all (except occasionally for safety reasons), and all of this would have alleviated the burden on section rangers and allowed them more time to address other, arguably more important, issues. The fire management policy described here can further be seen as an improvement over the 2001 iteration as it does not advocate a homogeneous approach to fire management over what is a large and variable region. It has rather defined separate ecological objectives and management actions for different LFMUs within the KNP, based on ecological and biophysical features rather than administrative boundaries. The new policy also takes a step towards linking fire regime patterns to expected ecological outcomes, which are different for five distinct zones within the KNP. In so doing, it sets the basis for the formulation of clearly-related ecological thresholds, and for a meaningful assessment of the effects of fire. Finally, it recognises the futility of a "command-and-control" approach that would seek to impose a particular fire regime on the landscape, and is guided rather by historic fire patterns that would be more achievable.

We recognise the apparent potential circularity of basing desired fire regimes on their historic prevalence, as it could simply perpetuate problems of the past. Overall historic fire regimes may also mask potential differences between successive policies. The counter-argument to these criticisms is that we now recognise differences that are inherent in particular landscapes (LFMUs), thus avoiding a one-size-fits-all approach to fire management. We accept that some areas are clearly not fire-prone, and that attempts to impose a fire regime on them will not succeed. In other landscapes, we have suggested deviations from the historic means, calling for more frequent fires in sourveld and less frequent fires on basalt. Successive policies also demonstrably had little effect on fire return periods (van Wilgen et al., 2004). Even if management were able to influence the fire regime to a large degree (for example by increasing the heterogeneity of fire intensity patterns), there is very little understanding of how this would affect ecological outcomes (Parr and Andersen, 2006). We therefore reasoned that the promotion of a zone-specific fire regime that is demonstrably achievable and simultaneously not demonstrably harmful would be the best course of action. It would reduce the work-load associated with burning where such burning was arguably not needed, and it would provide an opportunity to test assumptions about influencing ecological outcomes by explicitly linking outcomes to assumed fire-related drivers.

We also recognise that, while the KNP's overarching goal is to "maintain biodiversity in all its natural facets and fluxes" (van Wilgen and Biggs, 2011), the focus of fire management is still largely on range condition (as a means to support large grazing herbivores) and tree conservation (Table 1). This could be interpreted as a legacy of a historic focus on 'game' management, which persists today because of importance of large mammalian herbivores (and their predators) for tourism, which is in turn the largest generator of conservation funds. This focus remains important also because there are few indications that the current fire regimes are having any adverse effects on other components of biodiversity (van Wilgen et al., 2007).

5.4. Future challenges

Our assessment suggests three areas in which a better understanding would be needed to further improve fire management in the KNP:

- Further research to inform modifications to fire management policies;
- A consideration of whether policy proposals are implementable in practice; and
- The need to resolve competing or contradictory objectives.

Research is needed because the many concerns expressed by section rangers (for example, that fires are too frequent or too intense on basalt substrates, or that reductions in fire intensity will reverse the trends in large tree mortality) are essentially hypotheses that need to be verified through field studies. In the case of bush encroachment, research is still needed to assess whether the few high-intensity fires that have deliberately been applied have had the desired effect of reducing the cover of woody shrubs, which will in turn require multiple applications of the treatments, and monitoring of the vegetation responses. In the case of the impacts of fire on large trees (zone 3), it is again unclear whether, and to what extent, a reduction in fire frequency or intensity would slow, halt, or reverse the high levels of mortality in large trees. In addition, the levels at which thresholds have been set are no more than first approximations, and their accuracy needs to be established. Currently, they serve to focus the manager's attention on what are thought to be important issues that would otherwise be overlooked, and it is fully recognised that they may need to be refined and adjusted as knowledge and experience accumulate. The assumption that there is a strong relationship between rainfall and the extent of fires, used to estimate burning targets for LFMUs, was derived from data at the scale of the entire KNP (van Wilgen et al., 2004). This relationship holds at larger scales (Archibald et al., 2010b), but we found it to be weak at the scale of LFMUs, suggesting that the relationship may break down at finer scales, and that more appropriate predictors of burnt areas need to be developed. Finally, the relative role of fire in determining ecological outcomes needs to be better understood. It may well be the case that fire plays a relatively minor role compared to other important drivers (Fig. 2), in which case managing fires should become less of a priority (as it has in the case of zones 4 and 5 in the policy described here). Up to now, there has been no attempt to link ecological outcomes either to fire alone, or to multiple interacting drivers, and this needs to be done.

The question of whether or not policy proposals are implementable in practice, at a large scale, and over multiple fire cycles is also important. For example, while thresholds for the area burnt in high intensity fires have been suggested to counter bush encroachment, it is simply not known whether the thresholds are appropriately scaled to ensure that ecological objectives would be met. Should repeated high-intensity experimental fires have the desired effect, it would then also be necessary to estimate how much high-intensity burning would be required to reverse bush encroachment trends over a very large area (probably hundreds of thousands of ha in zone 1 and possibly zone 2). Conducting repeated high-intensity burns over a large area would be contentious and expensive, given the risk that they undoubtedly pose to wildlife and infrastructure, which in turn would require careful planning and execution.

Finally, achieving different management goals may require the implementation of contradictory interventions. The deliberate implementation of high-intensity fires, aimed at reversing trends in bush encroachment in zones 1 and 2, would require section rangers to exceed burning prescriptions aimed at promoting safety, and would be in contravention of legal bans on such fires (see, for example, van Wilgen et al., 2012). Attempts are currently being made to resolve this issue, or at least to reach a compromise, but the tension between achieving the goals of safety and ecological benefits will continue to bedevil fire management in future. There is also a desire to reduce fire intensity in some areas, both in the hope that it will reduce the mortality of large trees, and allow saplings to escape fire and grow into fire-resistant larger size classes. This would in turn reduce the opportunities for section rangers to conduct the high-intensity fires needed to counter bush encroachment where the two problems co-occur. One solution may be to separate the achievement of these two goals spatially, applying appropriate but different treatments to separate areas. Clearly the matter will require more thought and refined guidelines for fire management.

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