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Research, monitoring, and reflection as a guide to the management of complex ecosystems: The case of fire in the Kruger National Park, South Africa

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Abstract

Conservation managers frequently set goals and monitor progress toward them. This often becomes a routine annual exercise, and periodic reflection over longer periods is done less often, if at all. We report on the annual monitoring of fire patterns in the Kruger National Park between 2012 and 2020, and examine how these compared with desired thresholds of spatial extent and intensity. These thresholds were based on decades of research and were aimed at achieving specific ecological outcomes. The patterns were outside of thresholds in two out of five fire management zones. In one (Zone 1), the goal was to encourage frequent burning, and this was marginally not achieved due to a severe drought during the period assessed. In Zone 3, a reduction in extent and intensity was desired, but thresholds for both were substantially exceeded. An exceedance in any given year might not trigger a management response, but if this occurs over multiple years it should trigger an examination of whether these exceedances affected the desired ecological outcomes. On reflection, we recommend that current management in four zones need not change, but that Zone 3 would require appropriate interventions. The available options can simultaneously produce positive and negative conservation outcomes, so trade-offs become necessary. By reflecting on research findings and management challenges, the advantages and disadvantages of available options have become clear, providing a basis for prioritization and compromise.

KEYWORDS

adaptive management, elephants, fire intensity, rhinos, savanna, trees

1 | INTRODUCTION

Managers tasked with maintaining ecosystem health and biodiversity in protected areas are expected to use scientific evidence to design management interventions aimed at achieving specific goals (Downey et al., 2021). However, natural ecosystems are highly complex, and their structure and composition are determined by interacting and variable natural processes such as precipitation, herbivory, predation, and fire, as well as by anthropogenic effects, including management interventions. Managers therefore often have to make decisions even though information or understanding is incomplete. It is thus necessary to monitor progress toward goals, and to adjust management if goals are not being met, a process known as strategic adaptive management (Holling, 1978; Rogers & Biggs, 1999). The relevance of the goals and the options and tools available to achieve these goals also need to be re-examined from time to time as new scientific evidence emerges or as societal expectations change (Gillson et al., 2019). Where adaptive management systems are in place, monitoring results are normally assessed against the goals, often on an annual basis, and this becomes a routine activity that does not always trigger an immediate management response if goals are not met in the short term. It is therefore necessary to purposely take the time to reflect on the achievement of goals over longer periods (Biggs et al., 2011), when trends may become clearer, and the need for changes to management more apparent. Fire management provides an example of such a process, and here we aim to provide a longer-term reflection on the achievement of fire-related goals and what it might mean for future fire management.

Fire is an important ecological process in African savanna vegetation, where it plays a central role in determining the structure and composition of these ecosystems (Bond & Keeley, 2005; Higgins et al., 2007). Fire is therefore a process that needs to be managed, and fire management has been constantly adapted over the past century as our understanding of its ecological role improved (Nieman et al., 2021; van Wilgen, 2009). Fire can be used to achieve specific goals, and Nieman et al. (2021) identified 10 broad goals of fire management in savanna protected areas in Africa. These included ecological goals (protecting large trees, maintaining range condition and biodiversity, reversing woody encroachment, and controlling invasive alien plants and disease vectors) as well as social goals (protection of infrastructure, ensuring safety, reducing greenhouse gas emissions, maintaining community relationships, increasing visibility for tourism and policing, and allowing for harvesting of natural resources).

Managers in the Kruger National Park, South Africa (hereafter KNP), have long recognized the importance of fire, and have sought to ensure that fire continues to play an appropriate role in the conservation of the park's savanna ecosystems. The way in which fire has been managed in the KNP has changed over time as science provided new insights, and as new philosophies emerged (Biggs & Potgieter, 1999; van Wilgen et al., 2008). Fire regimes (i.e. the characteristic range of fire return intervals, seasonal occurrence, intensity, and size of fires, Gill, 1975) can be highly variable, and fire management in the KNP attempts to cater for this variation by allowing elements of the fire regime to vary within pre-defined limits, termed "thresholds of potential concern" (Biggs & Rogers, 2003; van Wilgen & Biggs, 2011). Thresholds relating to fire return periods, the seasonal distribution of fires, the range of desired fire intensities, and the size-class distribution of fire scars were first proposed in 1997 (van Wilgen et al., 1998). If a threshold is exceeded, then management could be adapted to bring the system back to within the desired range, or the threshold could be recalibrated if the proposed range is clearly unattainable, if the management goals change, or if new knowledge suggests that the thresholds need adjustment.

Initially, fire-related thresholds were assessed at the scale of the entire KNP, but in 2012 the park was divided into five fire management zones ranging in size from 40,000 to >600,000 ha (van Wilgen et al., 2014), and thresholds for elements of the fire regime were then developed separately for each fire management zone, taking the differential effects of fire in each zone into consideration. These thresholds were defined by identifying whether there was cause for concern regarding the effects of fire in any of the zones, and considering what fire regime would be most appropriate for addressing the concerns that existed. Desired ranges for elements of the fire regime were in turn based on decades of ongoing research. Science, through applied research and monitoring, therefore plays a critical role in (1) identifying and quantifying the concerns, (2) suggesting potential solutions, and (3) evaluating the outcomes from the implementation of the proposed solutions. Each of these three were integral components in our case study of fire management in the KNP:

- *Concerns*: Past research has raised two broad concerns that are directly influenced by fire, namely that woody encroachment is increasing in the high rainfall zones of southwestern KNP (Buitenwerf et al., 2012), and that tall trees are being lost on the fertile basaltic plains (Asner & Levick, 2012; Eckhardt et al., 2000; Trollope et al., 1998; Viljoen, 1988).
- *Potential solutions*: Woody encroachment can be addressed by increasing fire frequency (Higgins et al., 2007; Smit et al., 2010), while a reduction in fire frequency may be needed to allow shorter trees to develop into taller, fire-resistant height classes (Trollope et al., 1995). High-intensity fires have potential for reducing woody encroachment in the short term, but result in the loss of tall trees (Smit et al., 2016). As such, the scientific evidence suggested that frequent, high-intensity fires may be an appropriate fire regime for reducing woody encroachment in high rainfall zones of southwestern KNP, but that

fewer and possibly lower intensity fires may be more appropriate for reducing tree loss on fertile basaltic plains.

- *Evaluation*: Van Wilgen et al. (2014) carried out a retrospective assessment of fire patterns between 2002 and 2012, to examine whether the frequency and intensity thresholds in each of the fire management zones had been exceeded prior to the delineation of the zones. They concluded that, with a few exceptions, patterns had largely remained within the pre-defined thresholds, and that encouraging a fire regime that remained within these thresholds should be achievable. Since then, the fire regimes have been monitored on an annual basis, with the findings being reported to and discussed annually with managers in the context of comparing them to the thresholds, but no changes have been made to official fire management policy since 2012.

In this paper, we report and reflect on an assessment of patterns in the KNP's fire management zones between 2012 (when a zone-based approach was initiated) and 2020, and discuss the factors that will affect appropriate responses in cases where thresholds are exceeded.

2 | METHODS

2.1 | Study area

The KNP (established in 1896 and proclaimed as a national park in 1926) is situated in the low-lying savannas of the eastern parts of the Limpopo and Mpumalanga provinces of South Africa. The park covers 1,948,528 ha, with elevations from 260 to 839 m above sea level, and mean annual rainfall between 350 and 750 mm. The park is crossed by seven perennial or larger seasonal rivers that run from west to east, and is underlain by granites in the west and basalt in the east. The vegetation can be divided into woodlands on granite in the southwest, open wooded grasslands on basalt in the southeast, poorly grassed woodlands (dominated by the mopane tree *Colophospermum mopane*) on granites in the northwest, and multi-stemmed mopane woodlands (1–2 m) on basalt in the northeast. The granite and basalt areas are separated by a relatively narrow shale band in the south. The park contains 147 mammal species, including large herbivores [elephants (*Loxodonta africana*), hippopotami (*Hippopotamus amphibius*), buffaloes (*Syncerus caffer*), and rhinos (*Certatotherium simum* and *Diceros bicornis*)], as well as a range of other grazers [e.g. zebras (*Equus quagga*) and blue wildebeest (*Connochaetes taurinus*)], browsers [(e.g. kudus (*Tragelaphus strepciceros*) and giraffes (*Giraffa camelopardalis*)], mixed feeders [e.g. impalas (*Aepyceros melampus*)], and large predators [(e.g. lions (*Panthera leo*), leopards (*Panthera pardalis*), painted wolves (*Lycaon pictus*), and spotted hyenas (*Crocuta crocuta*)]. Grazing herbivores and fire are essentially competitive consumers of grass fuels, so decreases in herbivore numbers can lead to increases in fire and vice versa (Smit & Archibald, 2019), while browsing and bark damage by elephants can increase the mortality of trees after fires (Vanak et al., 2012).

2.2 | Fire management zones and associated fire regime thresholds

Following the adoption of a revised fire management policy in 2012, the KNP was divided into five fire management zones based on differences in geology, mean annual rainfall, and historically recorded fire return

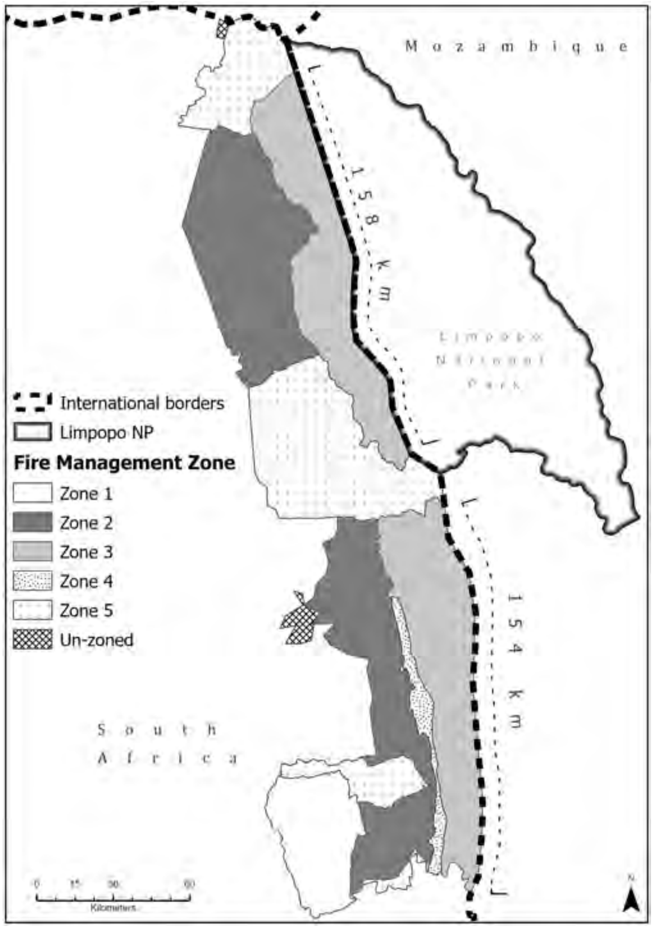

FIGURE 1 Fire management zones in the Kruger National Park (KNP). The map also illustrates the long international border between the KNP and Mozambique, including the adjacent Limpopo National Park, from where fires frequently cross into the KNP

periods (Figure 1; Table 1; van Wilgen et al., 2014). These zones differ in several important ways that would necessitate differential approaches to fire management. These include differences in rainfall (which affects fuel accumulation and thus fire frequency), geology (which affects the palatability and productivity of grasses and their removal by herbivores, thus also influencing fuel accumulation and fire frequency), and landscape position (with areas closer to rivers experiencing fewer fires due to increased herbivory) (Smit & Archibald, 2019). The goals of fire management differ between zones, and within each zone, thresholds were set to maintain the extent and intensity of fires above or below a single threshold value so that they would promote the achievement of the goals of fire management (see Table S1 for details of fire regime thresholds; for full details of the rationale for zones and thresholds, see van Wilgen et al., 2014).

The approach of using a single threshold value as proposed by van Wilgen et al. (2014) was not strictly aligned with the adaptive management philosophy in which the status of the ecosystem is allowed to fluctuate between what are regarded as tolerable upper and lower limits (Biggs & Rogers, 2003). It therefore became evident during this review that the thresholds should be reformulated to include upper and lower limits. Within these limits, the area burnt and the intensity of fires

TABLE 1 Salient features and broad objectives of fire management in five fire management zones in the Kruger National Park (after van Wilgen et al., 2014)

Fire management zone	Area (ha)	Features	Broad fire management objectives
Zone 1. Sourveld on granite	150,699	Savanna in areas with relatively high mean annual rainfall (~750 mm) and low-nutrient soils, which drives high fuel biomass resulting fire return periods of 2–4 years	Maintain forage quality and reduce woody encroachment by burning frequently Halt or reverse encroachment by woody plants by allowing occasional high-intensity fires
Zone 2. Savanna on granite	628,278	Savanna woodlands occurring on relatively complex topography with numerous granite outcrops and drainage lines, resulting in heterogeneous fuel conditions. Fires occur at return periods of 3–6 years	Prevent ongoing loss of tall trees, and allow tree saplings to progress to fire-resistant size classes where appropriate, by igniting prescribed fires earlier in the dry season so as to reduce the extent of high-intensity fires in the late dry season. In other areas, use high-intensity fires to control woody encroachment. Managers are allowed to decide where these competing interventions would be appropriate
Zone 3. Savanna on basalt	602,943	Open wooded grasslands or shrublands on relatively flat topography underlain by comparatively nutrient-rich soils derived from basalt. Fires occur at return periods of 2–5 years	Maintenance of acceptable range condition through appropriate use of fire Prevent ongoing loss of large trees, and allow for recruitment of tree saplings into more fire-resistant age classes by reducing fire frequency and intensity
Zone 4. Savanna on shale	43,935	High cover of woody plants and high levels of herbivory due to palatable grasses. Low biomass of grass fuels results in the area burning only rarely	Protect infrastructure from occasional rare fires by burning in limited areas to reduce fuel loads where needed Due to its long and narrow configuration and low fuel loads, Zone 4 is utilized as a firebreak separating zones 2 and 3
Zone 5. Areas adjacent to riparian zones	473,137	Proximity to rivers leads to high levels of herbivory by large, water-dependent herbivores and low fuel loads. As a result, these areas seldom burn	Protect infrastructure from occasional rare fires by burning in limited areas to reduce fuel loads where needed

would be acceptable (see Table S2 for a rationale for the proposed upper and lower limits). We then re-assessed fire patterns against the new proposed limits to determine whether there would be any cause for concern (Tables S1 and S2 present details of the assessments of fire regime patterns against the original single thresholds, and the subsequent upper and lower limits respectively).

2.3 | Application of prescribed fires

The KNP is divided into 22 ranger sections, and ranger sections are further divided into smaller units ("burning blocks") for the purposes of prescribed burning. The burning blocks are typically delineated by roads or rivers, which act as fuel breaks between burning blocks. Prior to the commencement of the fire season (in April), each section ranger is assigned a guideline target area to be burnt during the fire season. The guideline target area is estimated from a strong 45-year linear relationship between antecedent rainfall over the previous two rain seasons and area burnt (van Wilgen et al., 2004). Annual rainfall varies considerably between years, and the amount of rain that falls influences grass fuel production and the area that burns in a given year. For example, an average annual rainfall of 400 mm over two successive years would result in ~6% of the KNP being burnt, whereas an average rainfall of 1000 mm would result in ~45% of the KNP being burnt. The predicted area is used to set an initial target area to burn in the coming fire

TABLE 2 Fire regime and ecological outcomes in five fire management zones in the Kruger National Park between 2012 and 2020

Fire management zone	Fire regime thresholds	Fire regime and ecological outcomes
Zone 1. Sourveld on granite	The area burnt each year should be within pre-determined limits above and below the area predicted to burn based on antecedent rainfall	The area burnt was marginally below the target range in some years, because of a severe drought during the period assessed. Ecological outcomes (large trees numbers, woody plant density, and forage quality) are not formally monitored due to a lack of capacity, but ongoing research indicates that the number of large trees continues to decline due to ongoing interactions between fires and elephants
Zone 2. Savanna on granite	This zone is topographically heterogeneous, and it is assumed that this will result in equally heterogeneous fire patterns, and that monitoring of these patterns would not be necessary	Elements of the fire regime are not monitored Ongoing research indicates that the number of large trees continues to decline
Zone 3. Savanna on basalt	The area burnt each year should be kept below half of that predicted to burn from antecedent rainfall, and less than 10% of the area should burn in high-intensity fires	Fires routinely burnt more than the desired target area, and extent of high-intensity fires exceeded the target area in some years. Attempts to break up fuel loads with early dry season burning have failed to prevent large areas from burning in the late dry season Ongoing research indicates that the number of large trees continues to decline
Zones 4 and 5. Savanna on shale, and areas adjacent to riparian zones	Given that these zones seldom burn, a *laissez faire* approach is adopted to fire management, and a very low threshold is set to allow for fuel reduction burns around infrastructure	The area burnt remained below tolerable levels in all years. Ecological outcomes are largely independent of fire

Note: See Tables S1 and S2 for full details of fire regime thresholds and outcomes.

season, and targets are then adjusted to suit the specific fire management zone (see Tables 1 and 2). Park scientists also compile an annual report that assesses all fires that occurred between April of the previous year, and March of the current year, in which patterns of extent and intensity are compared with thresholds. This provides an opportunity for managers and scientists to discuss the guideline targets and to compare them to the preceding year's patterns.

Data on antecedent rainfall were collected from 23 rainfall stations across the park for the years 2010–2018 to estimate the guidelines for area to burn each year from 2012 to 2020. Each estimate for area to burn in a given year was based on the rainfall of the preceding 2 years, e.g. the target area to burn in 2012 was based on rainfall in 2010 and 2011. The guideline target areas are adjusted in some zones so that area burnt would remain within a desired range (for example, the area burnt should not exceed 50% of the area predicted to burn in Zone 3, and no burning targets but upper thresholds for accidental fires are set for Zones 4 and 5, see Table S2). The guidelines for burning within a given ranger section can also vary in ranger sections that include more than one fire management zone. Progress towards targets is monitored throughout the fire season, and prescribed burning targets are adjusted as unplanned fires occur, so that the total area burnt stays within the thresholds. Due to a severe drought in 2015 and 2016 (Malherbe et al., 2020), a decision was taken not to conduct any prescribed fires in 2016.

2.4 | Estimates of burnt area and fire intensity

The area burnt in each fire management zone was estimated for each year from 2012 to 2020 using the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite-derived imagery. An estimate of Byram's (1959) fireline intensity was assigned to each fire, using the classes proposed by Attorre et al. (2015) as follows: high (>1650 kW m^{-1}), moderate (1200–1650 kW m^{-1}), or low (<1200 kW m^{-1}). Estimates of fireline intensity were based on estimated fuel loads (in turn estimated from relationships between post-fire age and antecedent rainfall, see Govender et al., 2006) and the season of burn, as described by van Wilgen et al. (2008). The percentage of the area that burnt in each fire intensity class was then estimated from these data. In addition, the source of ignition for each fire was noted as either a prescribed management fire, a natural fire (i.e. ignited by lightning), unplanned fires started by people other than managers, fires that entered the KNP from outside the park boundary, or unknown (the source of ignition could not be determined).

2.5 | Interpretation of fire regime patterns in terms of ecological outcomes

The fire regime thresholds were designed as proxy measures for biodiversity conservation on the assumption that allowing the fire regime to fluctuate within acceptable spatial, temporal, and intensity limits would cater for the diverse needs of all species within the ecosystem (van Wilgen et al., 1998). In cases where thresholds are exceeded, the ecological outcomes associated with these deviations need to be examined. Ideally, ecological outcomes such as range condition, tree cover, and woody shrub encroachment should be monitored and assessed against thresholds of their own. Where these ecological outcome thresholds are exceeded, comparisons between causal factors (e.g. fire, herbivore populations, and climatic fluctuations or change) and ecological outcomes would be informative when debating potential solutions. These solutions could include either a change in management to restore the system to within a desired range, or a re-examination of the threshold to assess whether it was appropriate and/or achievable. In reality, though, while fire patterns can be assessed relatively easily and affordably, capacity constraints have not allowed for regular monitoring of ecological outcomes, which are many and varied, and would require intense field monitoring. Interpretation therefore needs to rely on the results of ongoing research projects that are not formally linked to the monitoring program, but where ecological trends are identified that could inform the development of potential solutions. Continued research is also needed to establish the relationships and test the assumptions between easily measured fire patterns as proxy for ecological outcomes.

3 | RESULTS

Regular annual reporting between 2012 and 2020 of the fire patterns in terms of the thresholds proposed by van Wilgen et al. (2014) revealed two zones in which thresholds were exceeded between 2012 and 2020 (Table 2). In Zone 1, there were 4 years in which the target area to be burnt was not achieved (Table S1). This would indicate that the vegetation in Zone 1 was not being burnt as frequently as desired, but, on average, the deviations were not large. The extent of burning was influenced by 2 years of extremely low rainfall (Malherbe et al., 2020), and a consequent management decision not to conduct any deliberate prescribed burning in 2016, resulting in few or no fires. In Zone 3, on the other hand, fires substantially exceeded the threshold for area burnt in seven out of 9 years (Figure 2a). The degree to which the actual area burnt deviated from the threshold (50% of area predicted to burn) did not follow any trend and varied from year to year (Figure 2b). The threshold for high-intensity fires was exceeded in 3 years. It would appear therefore that the vegetation in Zone 3 burnt much more frequently and at a higher intensity than desired, and in this case, the levels of exceedance were relatively high.

The re-alignment with both lower and upper thresholds meant that the threshold for annual area burnt in Zone 1 was below the desired range twice in 9 years, but these instances occurred after the severe drought that resulted in very low fuel loads. In Zone 3, the area burnt was above the desired range in 6 out of the 9 years examined. The area burnt was below the lower threshold in 1 year (in 2016 when a severe drought prevailed), and in 3 years the area burnt in high-intensity fires was above the threshold. The concern that Zone 3 may be burning too frequently, and at too high an intensity, remained valid under the re-aligned thresholds.

In terms of ecological outcomes, there has long been a concern that tree cover in the KNP has been declining (Eckhardt et al., 2000; Trollope et al., 1998; Viljoen, 1988). The interacting role of fire and increasing elephant numbers in driving these declines has been highlighted in more recent research (Asner & Levick, 2012; Vanak et al., 2012). Encroachment by woody shrubs, linked to rising levels of CO_2 in the atmosphere, has also recently become a concern (Buitenwerf et al., 2012), and the use of intense fires has been proposed as a way in which to counter this trend (Smit et al., 2016). Although unrelated to fire, rapid declines in the white rhinoceros populations due to ongoing poaching have introduced the need to use fires to lure these animals to areas of lower risk, as well as to increase visibility for policing (Ferreira et al., 2021).

4 | DISCUSSION

4.1 | The use of fire to achieve desired outcomes in African savannas

Fire regimes can be manipulated to achieve different outcomes by changing the frequency, season, intensity, and size of fires, and managers use fire to achieve multiple goals. In African savanna protected areas, these goals include ecological outcomes as well as social outcomes (outlined in the introduction above). There are also multiple options for the way in which fire can be used to achieve these goals, for example, by excluding fire, changing the season of burning, or influencing the spatial configuration or intensity of fires (Nieman et al., 2021). Fire management in African savannas is thus complex, involving the use of fire in multiple ways to achieve multiple, sometimes competing objectives. In addition, African protected areas seldom have adequate resources to both carry out management and to effectively monitor outcomes. In the KNP, the approach has been to monitor fire patterns and attempt to keep them within limits (thresholds) that would presumably adequately achieve ecological objectives and conserve biodiversity. Fire patterns can realistically be monitored at an affordable cost (e.g. in KNP, it is monitored using freely-available satellite imagery), and setting the thresholds has been based on the best available scientific understanding of the effects of fire (van Wilgen et al., 2007). Monitoring of ecological outcomes such as tree and woody shrub cover, or range condition, over large areas cannot realistically be afforded, so resource-constrained conservation

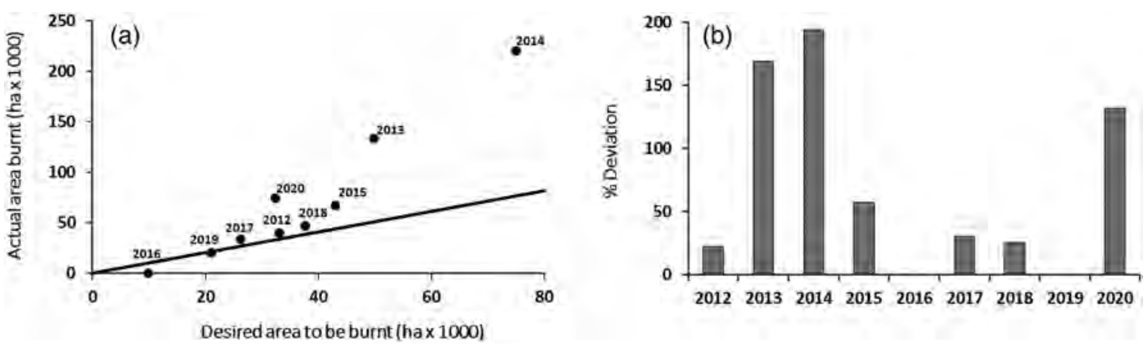

FIGURE 2 (a). Desired area to be burnt, and actual area burnt in 9 individual years in fire management Zone 3 (savanna on basalt) between 2012 and 2020 (dates of data points shown). The solid line represents parity, and data points above the line are years in which the desired area was exceeded, with distance between line and points indicating the level of exceedance. (b) The percentage deviation of the actual area burnt from the threshold (50% of the area predicted to burn) in successive years between 2012 and 2020 in Zone 3 (2016 was a drought year with almost no fire occurring) organizations such as KNP have to periodically test the founding assumptions in the light of recent research findings. Very few savanna protected areas in Africa have the resources to effectively implement scientifically-based fire management plans and to monitor their outcomes, both in terms of fire patterns as well as ecological effects resulting from complex, interacting factors. Even in relatively well-resourced and well-studied protected areas, such as Hluhluwe-iMfolosi in South Africa (Archibald et al., 2017), Serengeti in Tanzania (Eby et al., 2015), and Etosha in Namibia (Du Plessis, 1997), the lack of resources to monitor and understand outcomes is recognized as a constraint to improving fire management. The successful adoption of the process described here in other African savanna protected areas will depend on the availability of local research results as well as on the development and transfer of general principles from research within comparable savanna protected areas elsewhere.

4.2 | Responses to concerns revealed by monitoring

The adoption of a strategic adaptive approach to management in the KNP required the definition of thresholds of potential concern to guide management (Biggs & Rogers, 2003). Once a threshold is exceeded, it prompts an assessment of the causes of that exceedance, and whether a change in the management, or a re-calibration of the threshold would be appropriate. In the case of the review reported here, thresholds were exceeded in Zones 1 and 3, requiring an assessment of causes and reflecting on the need and feasibility of remedial management options.

Zone 1 did not burn as frequently as was desired, but the degree to which the thresholds were exceeded was small. The drought of 2015 and 2016 exacerbated this situation, as grass fuels were consumed by large mammalian grazers, and no prescribed fires were set in 2016. As a result, only 500 ha (out of 150,000 ha) burnt in Zone 1 in that year. On reflection, therefore, it appears that a change in management would not be necessary because the deviations were small and in line with prevailing climatic conditions.

Zone 3 burnt far more frequently and at a higher intensity than was desired, and the degree to which the targets were exceeded was large and variable (Figure 2). This might suggest that deliberate setting of prescribed fires should be discontinued, as they contribute to the target being exceeded, but managers argue that setting fires early in the dry season is still needed to break up fuels, and that they help to contain unplanned fires that occur later in the dry season. However, over 70% of the total area burnt in this zone between 2012 and 2020 burnt as unplanned fires, which included fires started by people both inside and outside of KNP, and fires ignited by lightning. Most of the unplanned fires were in August and September after the early dry season prescribed burning had started in June and July (Figure 3). The cause of most unplanned fires is unknown, but many of them originated outside of the KNP in the adjacent 1 million ha Limpopo National Park (LNP) in Mozambique, which shares a common boundary with KNP (Figure 1). Unlike KNP, about 25,000 pastoral herders live inside of LNP, where they burn the vegetation to provide grazing for livestock (Ribeiro et al., 2019). Managers in KNP have no jurisdiction in LNP, and can only attempt to prevent fires from crossing the border by maintaining a firebreak between the two areas. It has proved difficult to maintain this firebreak adequately, given the logistical challenges of assembling the necessary capacity and equipment, often at short notice when scarce suitable weather conditions for safe firebreak burning occur. It may be possible to prioritize this work to better maintain the firebreak, but the only other option to prevent excessive burning would be to attempt to break up continuous fuels by igniting as many patch burns as possible in Zone 3 in the early dry season. Whether or not this would be effective needs to be tested, especially since managers have indicated that the opportunities to do small patch burns in Zone 3 are limited. The landscape often contains high and rather homogenous grass fuel layers, making it difficult to contain fires even under relatively mild burning conditions.

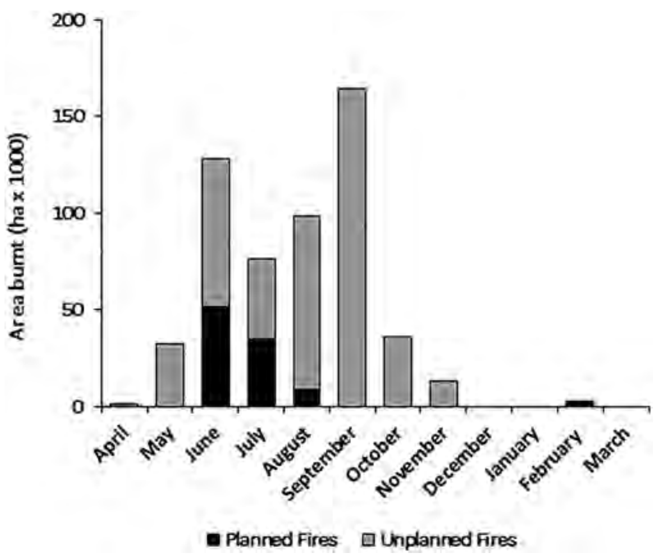

FIGURE 3 Total area burnt per month in fire management Zone 3 (savanna on basalt) between 2012 and 2020 in planned prescribed fires, and unplanned fires

4.3 | Current understanding of the role of fire

Fire-related thresholds were originally formulated in 1997 as a range of frequency, season, and intensity values, on the assumption (in the absence of an adequate understanding of the ecological effects of fire) that such a range would accommodate the diverse needs of ecosystems and their component species (van Wilgen et al., 1998). It was further noted that simultaneous monitoring of both fire patterns and trends in plant and animal populations could be used to identify interactions between fire and components of the ecosystem, leading to better-informed refinements of the thresholds if necessary (van Wilgen et al., 1998). Most of the understanding of the ecological effects of fire in the KNP arises from a long-term, plot-based fire experiment initiated in the 1950s (Biggs et al., 2003). Results from this experiment suggested that the park's ecosystems were largely resilient under a wide range of fire treatments, and that effects were most marked only in extreme treatments (repeated burning on an annual basis, burning repeatedly in the summer wet season, or total fire exclusion) (van Wilgen et al., 2007). For example, total fire exclusion resulted in a marked dominance by trees and shrubs (Higgins et al., 2007), and regular, frequent burning in relatively arid locations led to declines in herbaceous species richness and range condition (Smith et al., 2013; Trollope et al., 2014).

Fire intensities have been measured on the experimental burn plots since the 1980s (Govender et al., 2006), and these data have demonstrated that fire intensity has a significant effect on the ability of smaller trees to progress to larger, fire-resistant size classes (Trollope et al., 1995). The treatments applied to the experimental burn plots were fixed in terms of season and return periods. In reality, though, any site in the KNP will experience fires in different seasons, and at different return periods over time, and the experiment did not capture this variability. Data from the burn plots were nonetheless used to develop a model showing that variability in fire intensity over time is necessary for trees and grasses to co-exist (Higgins et al., 2000). This supported the notion that variability in the fire regime would be beneficial, and that the attempted imposition of more rigid set of return periods and intensities would not be desirable or practical.

Besides the findings from the experimental burn plots, additional research has demonstrated that tree damage by elephants increases the rate of mortality of tall trees after fires (Vanak et al., 2012), and that this rate of mortality also increases with increasing fire intensity (Smit et al., 2016). Regular fires prevent the short trees from developing into taller, fire-resistant age classes. Short trees and shrubs remain as an understorey to taller trees. Current mortality rates in the taller trees exceed replacement rates, resulting in marked declines in tall tree numbers and conversion of the vegetation to a low shrubland. On the other hand, protected areas where elephants are present experienced a net conversion of woodlands to grasslands. This amounted to 0.43% yr^{-1} in areas with elephants (i.e. woody encroachment was reversed) compared with a national annual increase in woody-dominated vegetation of 0.22% yr^{-1} (Skowno et al., 2017). In addition, Stevens et al. (2016) found that woody cover has doubled across South Africa over 70 years, but this was not the case in conservation areas with elephants. Elephants can potentially reverse encroachment by shrubs and shorter trees in fire-prone areas, by inflicting physical damage, removing bark protection, and exposing the wood to fires, resulting in shrub and sapling mortality. Woody cover can also be reversed by increasing the intensity of fires, at least in the short term (Smit et al., 2016) and under certain conditions (Scholtz et al., 2022). This understanding has informed the ongoing refinement of fire-related thresholds to guide management (van Wilgen et al., 2014), but there has been little in the way of simultaneous monitoring of ecosystem responses in the KNP. Regular monitoring of ecological outcomes and interpreting these in relation to fire patterns could have been informative, but capacity constraints have prevented this, and any future refinements will have to rely on the results of research projects that are often externally funded.

4.4 | Managing goals, choices, and trade-offs

In a review of adaptive management practices in the KNP, van Wilgen and Biggs (2011) plotted management issues along two gradients, namely complexity (difficulty of finding solutions) and impacts on biodiversity (from low to high). They concluded that the issue of interactions between fire and elephants could be placed in the quadrat for high complexity and high impact, making the issue "very important and difficult to solve." This review has confirmed that there are two additional issues that could be placed into that quadrat, namely increased encroachment by woody shrubs, and ongoing loss of rhinos through poaching. Encroachment by woody shrubs is driven by, inter alia, increases in global CO_2 (Buitenwerf et al., 2012), and could potentially be reversed by frequent, high-intensity fires (for example, by burning in the late dry season). Such a regime would, however, hasten the loss of tall trees, a process further accelerated by elephant damage to trees (Vanak et al., 2012; Figure 4). In addition, the white and black rhinoceros populations of the KNP are being seriously eroded by poaching driven by foreign demand for rhino horns. The white rhinoceros population has declined by 76%, from a peak of around 11,000 individuals in 2008 (at which time it represented approximately half of the world's population of this species) to around 2600 individuals in 2020 (Ferreira et al., 2021). This has become one of the most dominant conservation management issues in the park. Fire can be used to help manage the rhino problem in two ways. First, areas that are at high risk from poaching could be burnt to improve visibility for patrols and policing. Secondly, rhinos could be lured away from high-risk areas close to the park boundary by burning in "safer" areas deeper into the park, by attracting them to fresh grazing that appears after fire.

Managers thus find themselves literally between a rock and a hard place with respect to the use of fire. Reductions in the frequency and intensity of fires, and of elephant numbers, would seem like a potential approach to reduce the rate of tall tree loss (although tall trees declined under earlier and lower elephant densities, Trollope et al., 1998; Viljoen, 1988), so tall tree declines will likely continue even if elephant numbers are reduced. On the other hand, reductions in fire frequency and intensity could lead to ongoing woody encroachment, and reducing the number of elephants could trigger strong negative reactions, especially in the context of declining elephant populations in many other parts of Africa (Chase et al., 2016). Burning an effective firebreak on the KNP's eastern boundary may reduce the extent of cross-border fires, but the practice would attract rhinos to fresh grazing, exposing them to a higher risk of poaching closer to the park boundary. Managers may prefer to burn to lure rhinos away from the boundary, thus requiring a trade-off between preventing cross-border fires and reducing the risk of losing more rhinos.

In considering the future of fire management in the Anthropocene, Gillson et al. (2019) recognized that such management is complicated by interactions and feedbacks between social and environmental factors at varying temporal and spatial scales, and by uncertainty about the future. Our process of reflection has highlighted an inability to maintain fire regimes within a predetermined desired range for one of the KNP's fire management zones, as well as the complexities associated with addressing the issue. Besides the ecological uncertainties, several factors that are beyond the control of managers combine to make the imposition of desired conditions practically very difficult to achieve. CO_2 levels will continue to rise, and cross-border fires will continue to enter the KNP in the late dry season. While elephant numbers were controlled for many years in the KNP, this option remains controversial (Scholes & Mennell, 2008), leaving the manipulation of fire as a critical remaining tool. The application of two sequential burns to assess the effects of high-intensity fires on woody encroachment in one site (Smit et al., 2016) involved extensive planning and burning of firebreaks to prevent the experimental fire from escaping under very dangerous conditions. Although the outcome was positive in the short term

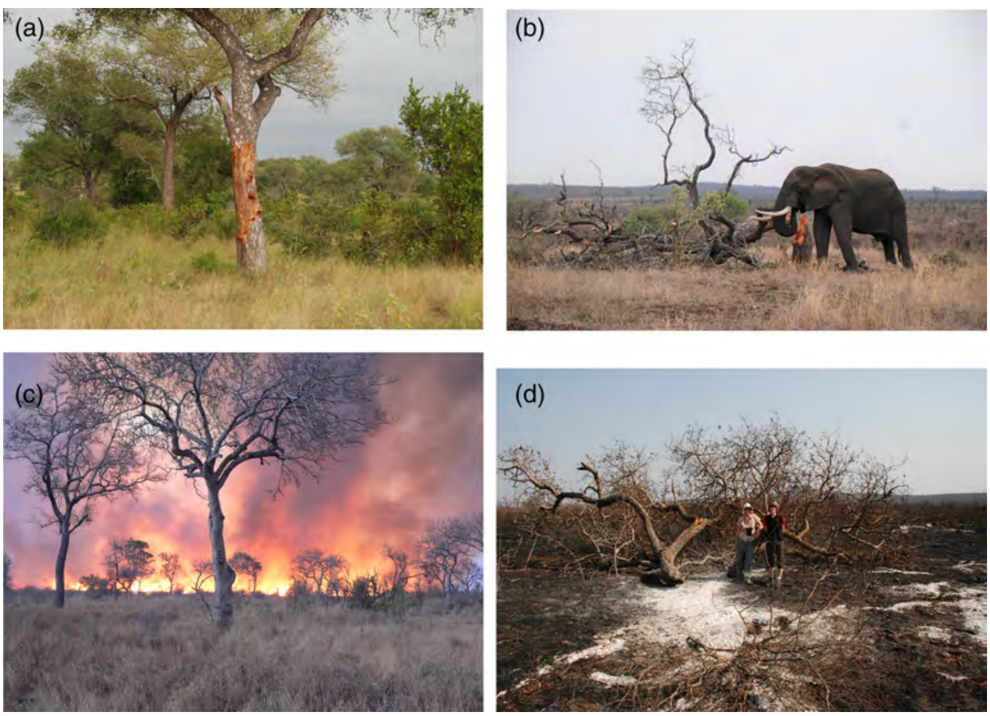

FIGURE 4 Interactions between fire, elephants, and tall trees. (a) Marula tree (*Sclerocarya birrea*) that has been ringbarked by elephants, exposing the trunk to further damage by insects and increasing vulnerability to fire; (b) Marula tree that has been toppled and extensively browsed by elephants; (c) high-intensity, late dry season fire on basalt plains (Zone 3), with Marula trees in the foreground; (d) Knobthorn (*Senegalia nigrescens*) that has burnt and collapsed after a high-intensity fire. Photo credits: (a), (b) and (d) – B.W. van Wilgen; (c) – Steven Whitfield

(woody shrubs declined in cover), this could not realistically be implemented at the scale that would be required to achieve the same effect across larger areas within the KNP, and potentially it could increase the mortality of tall trees. In addition, the short-term gains do not seem to remain over longer time periods (Scholtz et al., 2022). Biggs et al. (2015) discussed principles that should be included when aiming to sustain resilient ecosystems, one of which was to manage to maintain diversity and redundancy, which is captured in the KNP by allowing fires to occur across a wide range of return periods, seasons, size classes, and intensity.

Further principles proposed by Biggs et al. (2015) include the need to foster complex adaptive systems thinking, and to encourage ongoing and wide-ranging learning. Future management should draw on the best possible knowledge of available options and possible future scenarios for fire management, and this will require cycles of learning (Gillson et al., 2019). The first (single loop) learning cycle involves a process of implementation, monitoring, and adjustment, which has happened several times in the history of the KNP (Biggs & Potgieter, 1999; van Wilgen et al., 2008, 2014). A second (double-loop) learning cycle would involve additional stakeholders, and could include the consideration of "slow" variables and feedbacks (sensu Biggs et al., 2015) that may not become apparent from single-loop learning practiced at regular, frequent intervals. In the case of our study, such slow variables could include ongoing woody encroachment driven by steadily-rising CO_2 levels, and progressively declining tree numbers. Gillson et al. (2019) have suggested a triple-learning strategy in which insights should be sought by considering broader spatial and temporal aspects (such as long-term fire histories, traditional practices, ongoing global change, and changing societal expectations). It may be useful to consider these broader perspectives when designing fire management policies for the future. In the meantime, the system of monitoring and where necessary refining the thresholds should continue as new understanding emerges from ongoing research and periodic reflection. In the KNP, managers and embedded researchers regularly jointly debate the relevant issues as a team, and update thresholds and management responses (Gaylard & Ferreira, 2011; van Wilgen et al., 2016). Trade-offs will remain necessary, and as understanding develops, managers will hopefully be able to continue to make better-informed decisions about those trade-offs based on best available knowledge and changing context.

5 | CONCLUSION

The achievement of desired ecological outcomes through management interventions is not easy in a complex ecosystem where these outcomes are influenced by variable and interacting processes, changing social expectations, and where understanding is incomplete. As a result, managers often have to proceed as best informed by available knowledge and assumptions. In such an environment, it is important to approach these issues in a structured way by setting goals, monitoring progress towards those goals, and reflecting periodically on progress in order to properly close the learning loops. Although we have not identified clear solutions, the exercise reported here has required us to review current understanding and to be clear about the trade-offs that may be necessary. The case of fire management in the KNP provides a real-world example of the role and importance of periodic reflection that is necessary to advance understanding and to explicitly clarify and reflect on the nature of trade-offs that will have to be made.

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