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Patch-mosaic burning: a new paradigm for savanna fire management in protected areas?

C.L. PARR and B.H. BROCKETT

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The shift in ecological thinking, from equilibrium to non-equilibrium processes has been accompanied by a move to encourage heterogeneity rather than homogeneity in landscapes. Spatial and temporal heterogeneity is thought to be a major source of biotic diversity, and disturbances such as fire, producing heterogeneity are now recognised as being important. A patch-mosaic system of burning is based on the premise that fire pattern is a surrogate for diversity, and produces a range of patches in the landscape with unique patch characteristics and fire histories. A patch-mosaic system of burning is supported historically and empirically through field studies. However, there is a need for more research into the effects of various aspects of patch and fire variables on biotic diversity, especially in savannas where our understanding is particularly poor. Landscape-scale experiments, like those to be established in the Kruger National Park, South Africa are necessary to test different burning regimes. Challenges to patch-mosaic burning include determining the 'natural' range of variation for fire parameters, implementing random ignitions, and cost-effective fire scar mapping at the appropriate resolution. An adaptive management approach should be adopted to deal with the ignorance and uncertainties that characterise the management of savanna ecosystems. This should be applied with both modelling and monitoring as key elements in this process.

Key words: fire, adaptive management, biotic diversity, conservation, heterogeneity, modelling, patch dynamics.

C.L. Parr, Percy FitzPatrick Institute, University of Cape Town, Rondebosch, 7701 Republic of South Africa; B.H. Brockett, Pilanesberg National Park, P.O. Box 1201, Mogwase, 0314 Republic of South Africa.

Introduction

Fire, a major disturbance force, is regarded as a crucial determinant of savanna vegetation, and acts to modify broad patterns set primarily by rainfall and edaphic factors, and hence plays a role in determining the structure and function of these systems (Walker 1987; Scholes & Walker 1993; Scholes & Archer 1997). Despite the importance of fire in savanna systems being well established, fire management in protected areas remains a contentious issue, with considerable debate as to the most appropriate burning system. In most protected areas the main goal of conservation is the maintenance of biotic diversity and ecosystem functioning. A manager of a protected area faces a number of choices, and these decisions will result in different outcomes. Regarding fire management this is no different. For example a manager could aim to implement rigid fire regimes, or could vary the seasonality, and the frequency (by varying the number of ignitions per year, and the conditions under which they are ignited), and hence also the range in fire intensities. Thus through manipulation of fire variables it is possible to change spatial and temporal diversity, and determine whether biotic diversity is maintained. Decisions made to achieve objectives thus determine the outcomes produced. Where the maintenance of biotic diversity is the primary objective of a protected area, it follows that the fire management should be aimed at promoting a diverse fire regime (Mentis & Bailey 1990; Scholes & Walker 1993).

A patch-mosaic burning system was developed to maximise the benefits of a diverse fire regime for savannas, and is based on the premise that fire pattern is a surrogate for biodiversity (Brockett *et al. in press*). Using such a system the proportion of park burnt per year is a function of the grass fuel loads. Differences in rainfall both annually, seasonally and on shorter time scales (e.g. weekly) affect fuel characteristics e.g. distribution and compaction, fuel moisture, and fuel load. A patch-mosaic fire regime reflects this variation with randomly ignited fires spread over the seasons, and allowed to burn freely, unless a risk is posed to buildings or other structures, or the area to be burnt has been exceeded. This results in variation in size, number, location, seasonality and intensity of fires, and total area burnt per year.

This paper aims to examine the theory behind a patch-mosaic system, consider the empirical evidence supporting it and highlight research needs. Guidelines are offered to its implementation through adaptive management, with emphasis placed on monitoring and modelling.

The emergent heterogeneity paradigm

Previously much ecological thinking assumed that systems had a uniform structure, and that mechanisms that structured them were also uniform in space and time (Pickett & Rogers 1997). As a result homogeneity in the management of savannas was encouraged. Such management is regarded as a command-and-control culture, since the focus is on applying fixed prescriptions (Holling & Meffe 1996; Andersen 1999). Following major conceptual shifts in the understanding of savanna structure and functioning, the importance of inherent variability, a key characteristic in these environments, was recognised (importance of flux in addition to stability).

There remains much debate regarding the use of equilibrium theory, non-equilibrium theory, and disequilibrium concepts to explain savanna functioning (Frost *et al.* 1986; Westoby *et al.* 1989; Mentis & Bailey 1990; Scholes & Walker 1993; Illius & O'Connor 1999). Savannas are interpreted as event-driven systems (Walker *et al.* 1986), and the multiple stable state hypothesis for savannas proposes there may be two (or more) equilibria in these systems (Dublin *et al.* 1990). Disturbance events—such as fire, drought, rainfall, and herbivory—become the drivers necessary to overcome inertia between states (Mentis & Bailey 1990), and can affect a system's capacity to withstand impacts that may cause it to shift from one state to another, i.e. its resilience. Where periodic disturbance is essential to the resilience of a system, disruption of this disturbance regime can induce a loss of resilience (Holling 1981; Scholes & Walker 1993; Bullock & Webb 1995; Perrings & Walker 1997). Changes to savanna fire disturbance regimes via a prescribed block burning system, or via fire suppression (i.e. command and control strategies) result in reduced spatial heterogeneity. This results in simplification of the system, and consequently could reduce system resilience (Mentis & Bailey 1990; Scholes & Walker 1993; Holling & Meffe 1996).

Natural systems are typically patchy (Weins 1976), hence it is now recognised that spatial and temporal heterogeneity, and complexity are crucial elements in the functioning of ecosystems (Christensen 1997). With the paradigm shift from homogeneity and stability thinking, to patchiness in ecology, attention has focused on the development of patch theory, heterogeneity and patch dynamics (Weins 1997).

Variability, heterogeneity and patchiness are key elements in all system states, and as such, the effects of hierarchical, and dynamic patterns of heterogeneity are significant. Environmental patchiness (habitat and within-habitat diversity) is a major source of biotic diversity (Braithwaite 1996; Pickett & Rogers 1997). Huston (1994) describes how patchiness in pattern creates heterogeneity in resource availability, which then provides an array of opportunities for colonisation and survival. It is this existence of opportunities that maintains diversity. Individual patches support different species, or individual species require multiple habitat patch types. Species may breed, feed and shelter in different patches. Law & Dickman (1998) stress this is the case for many species of vertebrate that require multiple habitats to ensure different resources at different stages of their life-cycles. The same is also true for invertebrates (Usher & Jefferson 1991). Conservation of species requiring multiple habitats is thus enhanced in a mosaic environment.

Disturbances, such as fire, are important mechanisms for producing (and maintaining) spatial heterogeneity (Schwilk *et al.* 1997). Fire, therefore, plays a role in structuring ecological systems by producing a spatio-temporal mosaic of patches at different successional stages (Pickett & White 1985; Turner *et al.* 1994; Moloney & Levin 1996). It has been suggested that these diverse conditions may prevent community domination by one or few species (Bond & Van Wilgen 1996), and allow for the persistence of fire-sensitive species in a community subject to regular fires (Frost 1984). Forman (1995) considers a large area containing many patches in various stages of development as a 'shifting mosaic'. Patches will appear and disappear with each subsequent fire—a process that Baker (1992) refers to as 'patch population dynamics'. The character of such landscapes is determined by frequency, intensity, and spatial extent of disturbances creating patches, as well as the rate and nature of processes that result in patch succession (Christensen 1993).

The relationships between patch characteristics, fire characteristics, and landscape dynamics are complex and inter-related. Patch characteristics influence fire characteristics, which in turn influence patch characteristics in a complicated cybernetic system. Individual patches and fire events are also linked and affected by external factors such as climate. Climatic factors influencing fire behaviour vary in size and effects on a scale from months, to years to centuries. The periodicity of fire events is only partially determined by successional changes in the vegetation structure of patches (Binkley *et al.* 1993). In addition to successional changes in vegetation structure and composition, the likelihood of a fire, and patch characteristics are influenced by site history, position of a patch in the landscape, fuel load and fuel type, as well as topographical, geological and hydrological factors (Christensen 1993). Climate, ignition events, and the character of adjacent patches influence the likelihood of fire in a particular patch. Other determinants of vegetation patterns are the life-history characteristics of constituent species, previous site history, fire intensity (or severity), landscape mosaic, and the seasonality of fires. These factors are likely to result in shifts in the frequency distribution of different landscape patch types over time. Fire frequency may be regarded as a function of the available fuel (Van Wilgen & Scholes 1997), however this is not a simple relationship. This may be due to fuel properties, which in turn may affect variation in average fire-return intervals (Green 1982 cited by Christensen 1993). Also there is sometimes a spatial dependency between patches in a landscape, and this varies widely as a function of landscape structure, terrain, frequency of ignition events, and climatic conditions. These factors could result in variation in the fire parameters e.g. fire return periods. However, fragmentation of the landscape (for example road construction) might alter patterns of fire spread (Christensen 1993), and hence affect fire regimes.

Changes to 'natural' disturbance regimes constitute one of the major ways that humans have altered ecosystems, and thus the biological diversity that occurs within them (Bond & Van Wilgen 1996; White & Harrod 1997). Gill & McCarthy (1998) describe how there is growing concern (e.g. Keith & Bradstock 1994; Cary & Morrison 1995; Morrison *et al.* 1995) that in some Australian ecosystems regularity of burning (frequency, season, and spatial extent) could have adverse ecological effects. Hence fire management regimes that result in homogenisation of habitats should be avoided (Law & Dickman 1998). From a philosophical viewpoint, if nature is variable, any fire system aiming to mimic nature should incorporate this variability too. Gill & McCarthy (1998) and McLoughlin (1998) advocate that when managing ecosystems, the natural range of variation should be taken as the basis for fire management. Mentis & Bailey (1990) stress that fire parameters, such as fire interval, should be regarded as vectors (not scalars), where there is a frequency distribution of occurrence. In this way, ecosystem management acknowledges inherent uncertainty and ignorance, and attempts to accommodate it (Holling 1978; Christensen 1997). A burning regime that promotes heterogeneity and patchiness in the landscape is therefore preferable (Saxon 1984; Mentis & Bailey 1990; Russell-Smith *et al.* 1997).

Unfortunately, fire management in some Southern African savanna parks and in Australia land management agencies is still dominated by the command and control culture (Mentis & Bailey 1990; Anderson 1999). An alternative is offered in the form of a patch-mosaic burning system where fire parameters are varied to create a mosaic of patches representative of a range of fire histories which generates heterogeneity within the landscape (Brockett *et al. in press*). Such a burning system is based on the premise, that patchiness is a major source of diversity. It is assumed that if fire pattern is regarded as a surrogate for biodiversity, then a diverse fire regime, produced by the patch-mosaic system, should maintain biotic diversity.

Support for a patch-burn approach: a summary of historical and empirical research

Mosaics created by fire are thought to reflect historical burning strategies. Evidence from Australia, and to a lesser extent from southern Africa, suggests that the traditional burning regimes complemented the lightning fire regime. In southern African savannas, it is thought that early Man had been using fire for 1.5 million years, and the controlled use of fire for hunting and domestic purposes has occurred as early as the Stone Age, 250 000 BP (Brain & Sillen 1988). These lightning fires would generally occur during the rainy season (October to March). Native groups such as the Bushmen/San, !Kung, Swazi, and Zulu in southern Africa, and Aborigines in Australia used fire extensively throughout the year (early dry season to late dry season/spring) (Hall 1984; Braithwaite 1991; Braithwaite & Roberts 1995; Fensham 1997).

Early dry season fires were usually patchy and small in extent, increasing in size and intensity as grasses cured with the progression of the season. Small fires result in mosaic landscapes with patches of differing composition and structure, whereas large fires tend to homogenise a landscape (Binkley *et al.* 1993). Thus a traditional fire regime results in unburnt, early burnt and late burnt patches creating a landscape with a fine-grained mosaic of different seral stages (Short & Turner 1994; Van Wilgen & Scholes 1997). Further to the benefits of enhanced habitat diversity, an array of patch types can act as a natural firebreak, breaking up the front of large wildfires (Minnich 1983; Saxon 1984).

The decline and extinction of medium-sized mammals in Australia is thought to be related to a change in fire regime (Short & Turner 1994). With the movement of Aborigines out of desert areas, and the adoption of more urban lifestyles, the traditional fire regime previously imposed is being lost. It is thought that the fine-grained mosaic of different vegetation types that these species require, has not been maintained. Braithwaite (1991) advocates that in these areas fire management strategies should be based on traditional Aboriginal burning.

Botanical studies and modelling have revealed that static fire intervals may be detrimental (Keith & Bradstock 1994). Morrison *et al.* (1995) provide empirical evidence for variable fire intervals. Following analysis of plant-species compositions and recent fire histories, they conclude that it is likely that variation of inter-fire intervals through time is primarily responsible for the maintenance of biodiversity. In southern Africa it is thought that temporal variability in fire regimes promotes grass-tree co-existence, and hence the structural diversity of savanna systems (Higgins *et al. in press*). In North American forests too, it was found that the use of mean fire interval between fires (mean fire return period) could be quite misleading in predicting ecological response (Clark 1996). Gill & McCarthy (1998) conclude that variability in fire intervals in nature is inevitable, and indeed desirable in prescribed burning plans where the aim is to conserve biodiversity. They recommend the adoption of a variable system of fire application along with targeted monitoring.

Faunal studies too indicate that at the landscape level, the ideal fire regime for the conservation of a wide range of species is one where there are a variety of burns producing a mosaic of patches. Investigating the question of whether fire patterns could be used as a surrogate for biotic diversity, Parr (1999) studied the effects of post-fire fuel age and fire frequency on ant diversity in Pilanesberg National Park, South Africa. This study demonstrated that both time-since-fire (fuel age) and frequency of burning affected ant community composition. Post-fire fuel age and fire return period are only two variables considered in this study, and it is important to consider that there are many factors (e.g. intensity and seasonality of fire, patch size, shape and adjacent patch characteristics) not tested in this study that could contribute to the maintenance of diversity.

We conducted a brief scoping study to establish which aspects of fire (e.g. frequency, intensity, season), and patch parameters (e.g. post-fire fuel age and patch size) have been researched. It was clear that not all fire and patch parameters were covered in these studies. Furthermore, it was evident that certain taxa have been favoured for research: birds (Mentis & Bigalke 1981; Woinarski 1990; Brooker & Rowley 1991), reptiles (Braithwaite 1987; Lunney *et al.* 1991; Trainor & Woinarski 1994) and invertebrates, e.g. ants (Andersen 1991; De Kock *et al.* 1992; York 1994; New *et al.* 1996; Vanderwoude *et al.* 1997; Parr 1999) and grasshoppers (Chambers & Samways 1998). Most of these studies were based on changes in species composition and diversity (richness and abundance). This illustrates the paucity of information on faunal responses to burning, and serves to emphasise that there remains a pressing need for more studies investigating mammal, bird, reptile and invertebrate responses to burning, and the potential importance of variability in fire parameters and patch characteristics. Many fire studies are conducted opportunistically (e.g. following a wildfire through a fire exclosure), and there has been little research into the effects of extreme fire intensities which periodically stress landscape systems. As much of the research and quantitative evidence supporting the need to incorporate variability and heterogeneity originates in Australia, where fire ecology and management has perhaps advanced more rapidly than in southern Africa, there is a need to concentrate studies in southern African, and especially in savanna areas where little previous research has been conducted.

A key problem with many faunal studies is that the issue of scale is not addressed. Many fire studies are undertaken on small experimental plots where fires are often different in character to those occurring in larger, continuous areas. The problems associated with small plot size have been recognised (e.g. Gill *et al.* 1990; Carpenter 1996; Andersen *et al.* 1998) but still these studies persist. Although these studies are useful for improving our understanding, and may suggest that variability in burns is desirable, there is still a need for more objective calibration. This can only really be done by taking research a step further, and by testing these problems in the real environment and on a much larger landscape-scale. Hence the need for landscape-scale fire experiments (Anderson *et al.* 1998).

Implementing a patch-mosaic burning system and comparisons with other fire management systems

Determining the 'natural' range of variation of fire parameters is problematic. Acknowledging that fire intervals in nature occur with a varying frequency, Gill and McCarthy (1998) consider evidence for determining probability distributions of fire intervals. This is a complex procedure, and may be possible for some areas once life history traits of specific indicator species have been identified. However, determining specific indicator species is likely to require much research. Limits within which we should be working for specific fire variables (e.g. intensity, spatial extent and seasonality), need also to be determined and combined. Fire management policy should therefore be implemented to include as wide a range of variability as possible under the constraints imposed by alternative objectives. The variability that can be incorporated is often set not by the ecosystem but by the consumptive and/or non-consumptive use (e.g. tourism) of the protected area. An additional limit to implementing a wide range of variation in the fire parameters is the size of the protected area. The more extensive the area then the wider the range of variation in fire parameters that can be implemented.

Other burning systems may also produce patchiness and heterogeneity in the landscape. Lightning ignited fires will undoubtedly produce fires that are patchy in nature, however this patchiness differs fundamentally from that produced by a patch-mosaic system as fire occurrence is highly skewed towards the summer months. With a patch-mosaic system fires occur throughout the year, with greater variation in patch size as a result of the range of different conditions under which the fires are applied.

Under a prescribed block-burning system the area is divided into units for treatment (i.e. blocks or compartments), and these are burnt in a predetermined year according to schedule, and under controlled conditions, to create an equally-sized veld age mosaic (Seydack 1992). Such a system only promotes heterogeneity in the sense that the burnt areas or blocks may form a fixed mosaic. Blocks are not analogous to patches, as the mosaic is regular and uniform, both in space and in time. The mosaic produced by block burning therefore differs substantially to that produced by a patch-mosaic burning system as there is little variance in block size (hence fire size), or in the season and frequency of burn (e.g. Etosha National Park, Namibia (Stander *et al.* 1993; Du Plessis 1997)). Finally it should be noted that all burning systems produce fine scale patchiness to a greater or lesser degree e.g. small clumps of grass remaining unburnt after a fire.

There is a tendency to liken patches in a landscape to 'islands' in keeping with the equilibrium theory of island biogeography (MacArthur & Wilson 1967). When we consider the range of patch sizes in a landscape we might try to determine at which size threshold particular species drop in or out in an effort to ascertain the minimum (or maximum) patch size that is desirable. Thus, in this way we seem to be regarding patches as islands. How much like islands are patches? With the shifting dynamic nature of the landscape under a patch-mosaic system, patches are likely to be very different to real and fragmented habitat islands. Patches are often not isolated, distinct, tangible entities in the landscape with some obvious edge. There is much scope for research into how these patches function, inter-relate, are created and for how long they exist in the landscape.

A conceptual model was developed to illustrate how fire size may be determined by fuel characteristics (e.g. fuel size, distribution, compaction, and quantity), terrain, and the number of ignitions (Fig. 1). Fire frequency is a function of the: (1) fuel characteristics (e.g., the post-fire fuel accumulation rates), (2) terrain, (3) number of ignitions, and (4) season of burning. Some of these factors influence the rate of spread of a fire, and hence fireline intensities. Variation in fireline intensities results in a variation in fire size (Fig. 1). By applying fires in autumn (before the fuels are cured), the fireline

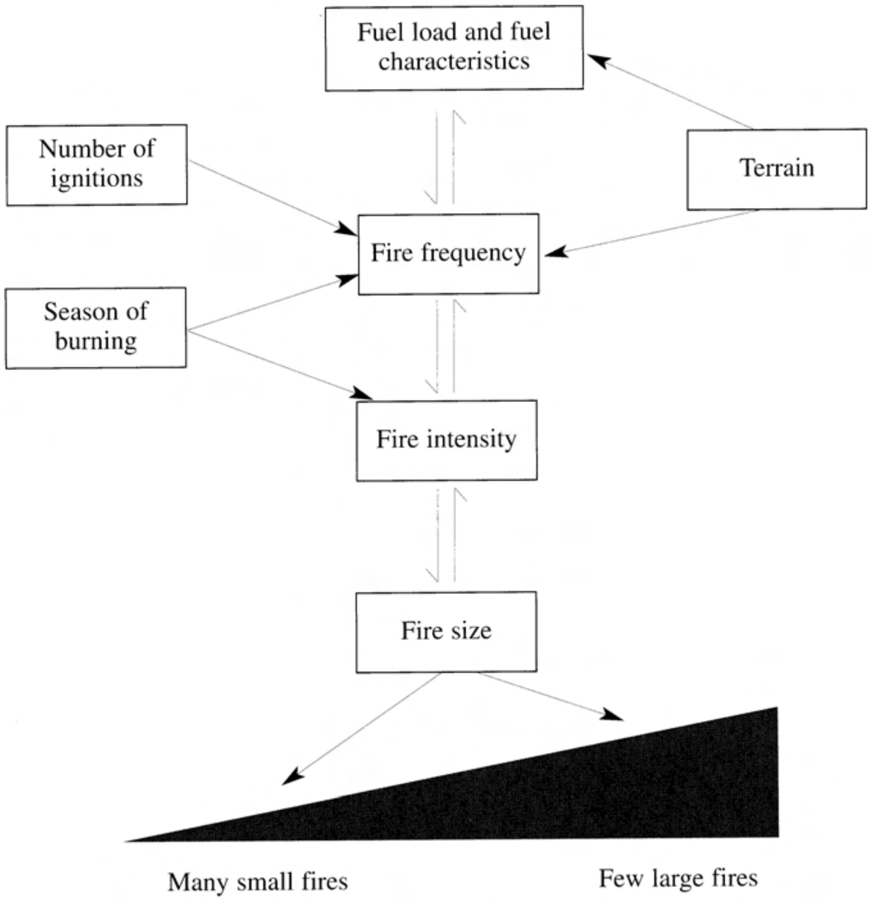

Fig. 1. Conceptual model for the interactions between fuel load, and fire parameters (seasonality, frequency, intensity, and fire size) in producing a continuum of fire sizes.

intensities would be reduced, and consequently also the fire size, and this would lead to many small fires. However, if fires were applied from late winter to early spring, then the mean fire intensity would increase, as would the mean fire size. Therefore, in applying a patch-mosaic burning system there are a number of choices to make with regard to: the number of ignitions per month (i.e. the seasonal distribution) and number per year; and the spatial extent of fires.

On the basis of present knowledge some choices may lead to unknown outcomes. In addition, there are a number of practical issues to be resolved. Some of the challenges are not unique to a patch-mosaic system, e.g. zonation. Practical issues to be addressed include the organisation of the ignition points; how a random design would function; and constraints imposed on management due to the zonation of the area (Table 1). Fire scar mapping is essential so as to make future decisions and to compile accurate fire statistics. With fire scar mapping it is firstly necessary to decide on the appropriate scale (Woodcock & Strahler 1987), and secondly, it requires research effort to evaluate new technologies in relation to their cost effectiveness (Thompson & Whitehead 1992). Remotely sensed data

Table 1

Challenges to the implementation of a patch-mosaic burning system in a protected area

Challenges
Random point ignitions
(1) *Patchy fuel load distribution* In arid fertile savannas in many cases the fuels may be below <1000 kg/ha, and at perhaps 50% of locations the fuel may be insufficient for a fire to spread (except under extreme fire weather conditions). A solution could be to use a stratified-random sampling design to select areas meeting fuel load criteria. Making such a choice will however result in a certain outcomes, and these would need to be evaluated.
(2) *Fuel moisture* Due to differential curing rates of fuels across a landscape, it may be difficult to ignite fires at the selected points in certain seasons.
(3) *Atypical locations* Obviously atypical locations such as rocky koppies, or steep slopes with little fuel should be excluded.
(4) *Grid-square size* Varying the size of the grid will affect the number of ignitions per unit area, and hence the resulting mosaic. Using a larger grid size will also enable greater choice to be exercised in selecting ignitions sites (this may help with low fuel load situations).
(5) *Map reading problems* In flat featureless areas in may be difficult for an operator to know whether he is in the correct grid square or not. The operator could use the GOTO function on a GPS to locate the centre of the grid square.
(6) *Zonation* The zonation (and hence the management) of the protected area may influence the method of ignitions used in certain zones e.g. wilderness zones. Certain zones may require aerial ignitions by helicopter.
Fire scar mapping
An essential requirement for the system is fire scar mapping after each fire. This information is required so as to make future decisions regarding whether to ignite further fires or not. In comparison with perimeter block burning systems where the mapping of fire scars are easier (as fires are ignited from roads) with the possible exceptions of wildfires. However, unburnt islands within block burns are often ignored.
Starting mosaic
The current attributes of the fuel mosaic will influence fire size. Therefore in order to establish a fire mosaic, special ignition rules and selection of fire weather conditions may be required initially.

limits management to specific scales by the very nature of the data. It is thus a combination of the spatial structure of the image and the viewed environment that determine the appropriate scales of observation (Woodcock & Strahler 1987). Mapping scales for each sensor vary considerably, and it is generally accepted that maximum operating scales for LANDSAT TM is 1:50 000, while NOAA-AVHRR 1:500 000 (Thompson & Whitehead 1992).

Applying an adaptive management approach to a patch-mosaic burning system

Scientific management involves the stating of clear objectives and their translation into goals, and making decisions to achieve objectives (Mentis 1984). A decision is a judgement; a choice between alternatives. According to Holling (1978) it is a myth that the goal of management is to produce policies that result in stable environmental behaviour. Our understanding of system function is poor, and hence it is impossible to minimise change and to eliminate the unexpected. In many systems unexpected or surprising management impacts are in fact necessary and essential system elements (Holling 1981; Holling 1995). Therefore reserve policy must recognise the inevitability of uncertainties, and the consequent selective risk-taking (Holling 1978). *Uncertainty* exists with respect to the outcomes of different scenarios in terms of their effects on biotic diversity. Savanna functioning is characterized by almost unique combinations and sequences of conditions involving moisture, nutrients, fire, herbivory, and other disturbances. Under the current state of knowledge, and for the foreseeable future, we are *ignorant* of the precise impact of these scenarios of events; save that diverse scenarios not markedly different from preceding ones allowing for persistence and coexistence of species should maintain the present spatio-temporal diversity of savannas (Mentis & Bailey 1990).

Adaptive management may be used to cope with problems associated with uncertainty and imperfect knowledge. There are a number of steps in a management process. The first step is the development of a clear set of objectives, and an operational strategy to achieve these objectives. This should be followed by an evaluation of the tasks and skills required, as well as the systems procedures and budget. The system should then be implemented, and the spatio-temporal diversity monitored, and the costs established. Both Holling (1978) and Walters (1986; 1997) argue that adaptive management should begin with a concerted effort to integrate existing interdisciplinary experience, and scientific information into dynamic models that attempt to make predictions regarding alternative policies. Modelling is therefore an essential and integral part of such a process, and has an important role in: (1) the clarification of the objectives and in enhancing communication, (2) the first attempt at understanding and evaluating the consequences of different strategies, (3) how to rank the outcomes in terms of the objectives, (4) identify what to monitor and how often, and what the limits to monitoring are, and (5) could be used to study what can and cannot be deduced from empirical studies. Mentis & Bailey (1990) use an adaptive management approach, to provide suggestions regarding the implementation of a burning system in a protected area. A monitoring system including the ecological (at appropriate spatial and temporal scales), economic and social outcomes, would need to be established to determine how effective the patch mosaic burning system was at maintaining biotic diversity.

The empirical approach would be long-term, and involves applying a policy for a patch mosaic burning system (see Brockett *et. al in press*), and monitoring spatio-temporal diversity over time. If monitoring revealed that the burning system was not performing satisfactorily, then there should be a review of this system (after an appropriate interval), and the whole process reviewed. An alternative application procedure should be selected, and the process repeated. Due to the ignorance arising from ecological processes and their interactions, field-management scale experiments are becoming popular to resolve such uncertainties at a landscape scale. However, this management by experimentation approach is generally costly, time consuming, and sometimes risky (Walters & Green 1997). A landscape-scale fire experiment was established at Kapalga, in Kakadu National Park, Australia (Anderson *et. al* 1998). In Kruger National Park, South Africa, a landscape-scale experiment (LASHFIRE) to test three fire management alternatives is to be established (Biggs & Potgieter 1999); included is a patch-mosaic burning system (Van Wilgen *et al.* 1998; Biggs & Potgieter 1999; Brockett *et. al in press*).

If landscapes are composed of a collection of patches undergoing successional change (Pickett & White 1985), then the character of such landscapes is determined by the frequency, intensity, and spatial extent of disturbances creating patches, as well as the rate and nature of processes that result in patch succession (Christensen 1993). Hence patch models which examine how a homogenous patch or strata changes through time could be developed. There are three types of patch model: (1) Markov (Noble & Slatyer 1981), (2) State-and-Transition (Westoby *et. al* 1989), and (3) Frame-based (Starfield *et al.* 1993; Starfield & Chapin 1996).

A Markov matrix of transition probabilities, based on patch demography, could be used to explore the long-term effect of fire regimes on vegetation structure, and composition, and for determining which demographic traits are critical for long-term success in frequently burned savannas (Christensen 1993; Hoffmann 1999). Patches in any particular state have a probability of being transformed during a particular time by successional change or disturbance into some other state. If the transition probabilities are fixed (i.e. the matrix is stationary), the equilibrium frequency distribution of states on landscapes could be predicted with simple matrix algebra (Christensen 1993). The fire regime which leads to the equilibrated proportions of states desired by park management could then be selected. This would help order options in a hierarchy of relative priority (Bell 1984). The priority choice could then be consulted iteratively and in greater detail to simulate the heterogeneity and fire parameter outcomes. This could be used to test an option (e.g. using a flowchart or algorithm as a decision-aid) prior to implementation (Mentis 1980).

Frame-based spatial modelling may also be advantageous as more complex and long-term simulations can be undertaken to determine the possible outcomes of different management policies. This may prove particularly useful when dealing with a patch-mosaic burning system where it allows for the exploration of spatial and temporal heterogeneity indices, and issues regarding different policy (e.g. limits of acceptable change required for the management and monitoring systems). Starfield *et al.* (1993) used this approach to investigate the interactions between rainfall, elephants, and fire in a *Brachystegia* woodland in Zimbabwe. However, such modelling does not include the mechanisms leading to changes. Christensen (1993) mentions that the nature of change of any particular patch is dependent on the characteristics of surrounding patches. Hence the need for spatially explicit simulation models. Such spatial dependency is recognised in most fire-spread models. Higgins *et al.* (*in press*) showed how variance in fire intensity interacts with plant attributes, making variance in fire parameters a key factor influencing the structure of savannas. Modelling paradigms that do not simulate the interaction between environmental variance and organism response are likely to give qualitatively different predictions.

Expert systems have the potential to synthesise current wisdom, and to simultaneously structure it to facilitate application to real world problems. The structuring of current knowledge in a form that facilitates its application aids the decision-making process. This also has the effect of rendering the knowledge testable. As with simulation models, the very attempt to synthesise and integrate knowledge is of great heuristic value. It follows therefore, that expert systems can facilitate the interface between the theory behind patch burning and its practise. Hence such systems could be developed for a number of purposes (Noble 1987), and at various stages of the adaptive management process (see Mentis & Bailey 1990). For example, Noble (1987) presents an expert system to model vegetation response to different fire regimes using a mixture of qualitative and quantitative rules, and Hoare (1985) working in Kakadu National Park, Australia, modelled the biological effects of fire on plant communities, using a fire behaviour and vegetation damage expert system. Davis *et al.* (1986) developed a fire behaviour expert system for Kakadu National Park. Bailey *et al.* (1993) present an expert system to facilitate consistent fire management decision-making in Pilanesberg National Park, South Africa. The development of expert systems leads not only to new applications, but also to new questions and modes of research (Starfield & Louw 1986).

Conclusions

Theory behind the patch-mosaic burning system appears intuitively appealing, and research thus far seems to support this approach. There are problems however with this system, both theoretical and practical, that must be addressed. We suggest the implementation of a patch-mosaic system through adaptive management involving modelling and monitoring phases.

The patch-mosaic burning strategy advocating a flexible, variable approach to fire management based on traditional burning practices offers a useful model (Saxon 1984; Rusell Smith *et al.* 1997). In southern Africa, the challenge of adopting similar burning systems has been taken up, most notably, by Pilanesberg National Park, South Africa. A system of prescribed burning combined with natural lightening fires has been implemented since 1989 with the aim of developing a patchy landscape mosaic (Brockett *et al. in press*).

It thus appears that through a patch-mosaic burning strategy, savanna fire ecology may be advancing into a new realm, with unexplored and exciting possibilities for research and management, with the continued protection and maintenance of biodiversity. It remains to be seen how long these ideas take to filter through to other fire-prone environments in southern Africa, such as the fynbos or the Drakensberg grasslands. It is possible however, that some environments where fire hazards are extreme may not be compatible with a free patch-burn regime (Morrison *et al.* 1996).

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