

THE EFFECT OF FIRE AND ELEPHANT ON VEGETATION	142
SUMMARY OF THE CURRENT KNP FIRE MANAGEMENT POLICY ADOPTED IN 2002	142
<i>Navashni Govender</i>	142
FIRE ELPHANT INTERACTIONS IN THE KNP	143
<i>Navashni Govender</i>	143
Fire management policy	143
Work in progress	143
Geology	143
Climate	143
Fire intensity and frequency controls the direct impact on vegetation, which will result in a specific vegetation state.	144
The impact that elephants have on vegetation is controlled by fire intensity and frequency.	145
FIRE EFFECTS OVER TIME.....	149
<i>Lindsey Gillson</i>	149
FIRE AND ELEPHANT INTERACTIONS IN SOUTHERN AFRICAN SAVANNAS	151
<i>Brockett B.H</i>	151
Fire impacts on woody vegetation.....	152
Mortality rates of woody plants.....	152
Interactions between elephant, fire and other factors	152
Models exploring fire, elephant and other interactions	153
References	154

THE EFFECT OF FIRE AND ELEPHANT ON VEGETATION

SUMMARY OF THE CURRENT KNP FIRE MANAGEMENT POLICY ADOPTED IN 2002

NAVASHNI GOVENDER

The fire management system being proposed for the Kruger National Park must satisfy the Park's recently revamped ecosystem objectives, which stress heterogeneity over space and time. The current intended lightning-driven system meant to achieve this, but proved to be dominated instead by fires caused by illegal immigrants. This led to revision, which was well underway before the tragic fire of 4th September 2001, an event, which served to help unify relationships between this, and KNP fire security policies.

Areas of continuing debate include understanding the implications of the role of early man in shaping the landscape with fire, as contrasted with justification behind demands for "hands-off" wilderness management. Cognisance has to now also be taken of the reality of concession areas and their need for smaller-scale fire heterogeneity patterns and lower levels of risk appropriate to their geographically more confined operations. Despite these challenges, much has been definitively learnt, for instance that point ignitions are preferable, that there should be limits on total extent allowed to burn (based in rainfall), and that the system employed must include enough cautiously thought-through variants to allow us to learn. The strategic adaptive approach is embedded in the proposed system by TPC's¹ being built into the proposed operations, two of the most important ones being measured and evaluated by rangers directly.

An innovative and seemingly practical way of uniting the best available components of patch mosaic fire philosophy with range condition and lightning fire philosophy, and embracing the reality of transmigrant burns, is proposed. It involves setting annual and monthly burn targets based mainly on vegetation measurements taken at the start of the season. Each month from early in the fire season, patch fires are put in by rangers towards a target also influenced by transmigrant fires. Adaptive "catching-up" or "slackening-off" is practiced as the season progresses, to try to keep somewhere near target. Rangers will generally stop setting fires at the onset of the lightning season to then allow lightning a chance to contribute as a natural source. Slight variations, to enable learning while managing, are imposed for wilderness areas, non-wilderness areas and concession areas, and other variations (such as amount of lightning influence in different areas) will arise over time as a natural contrast. Setting fires throughout the fire season will achieve a range of fire intensities.

In this way, lightning has the best safe chance of burning significant areas, instead of these areas being pre-empted earlier in the season by (often rampant) transmigrant fires. Generally, all fires are point ignitions. Wilderness areas are allocated the least invasive form of fire management, and concessions are given maximum safeguards permissible within a biodiversity management philosophy. Rangers will once again feel a sense of empowerment in fire management, and develop fire-setting skills. At all times during the learn-as-we-manage process described above, the central suite of TPC's operated in the KNP will act as the "referee's rules" for the desirability or otherwise of these systems.

¹ TPC's are Thresholds of Potential Concern, which are monitoring endpoints based on objectives describing the desired state for the Park. They are a variation on Limits of Acceptable Change (LAC's) and are discussed extensively in Box 3 page 14 of the Revision of the KNP Management Plan (Braack, 1997).

FIRE ELPHANT INTERACTIONS IN THE KNP

NAVASHNI GOVENDER

Overall framework

Fire has been identified as a scale dependant agent that affects elephant populations.

Fire was then broken up into two key components i.e. Intensity and Frequency. The following topics will be discussed in the executive summaries under the various chapters: Chapter 1: The effects of fire intensity and frequency is controlled by (a) the fire management policy, (b) geology and (c) climate. Chapter 2: Fire intensity and frequency controls the direct impact on vegetation, which will result in a specific vegetation state. Chapter 3: The effects of fire frequency and intensity on vegetation types is controlled by elephants as well as other herbivores, which are in turn controlled by the water provision policy.

The effects of fire intensity and frequency is controlled by (a) the fire management policy, (b) geology and (c) climate

Fire management policy

Recent analysis of the spatial database of all fires between 1957 and 2002 in the KNP was conducted to examine if elements of the fire regime (area burnt and the fire return interval) were influenced by the changes in the fire management policy (van Wilgen *et al.* 2004). Results show that (a) the area that burned in any given year was independent of the management approach and was strongly related to rainfall and (b) fire-return intervals was strongly influenced by the sequencing of annual rainfall rather than by management.

Work in progress

The effect of changing fire management policies on the intensity of fires (Govender *et al.*).

Key Publications

B.W. VAN WILGEN, N. GOVENDER, H.C. BIGGS, D. NTSALA, X.N. FUNDA. 2004 Response of Savanna Fire Regimes to Changing Fire-Management Policies in a Large African National Park. *Conservation Biology*; Volume 18, Issue 6, Page 1533-1540.

Geology

The decrease in woody cover observed on basalt soils (Eckardt *et al.* 2000) in comparison to the increase in woody cover on the granites can be contributed to the differences in fire intensity between the two soil substrata. This analysis of the influence of the two major geological substrates in the KNP is currently been conducted (Govender *et al.*).

Key Publications

ECKARDT, H. C., B.W. van WILGEN, & H.C. BIGGS. 2000. Trends in woody vegetation cover in the Kruger National Park, South Africa, between 1940 and 1998. *African Journal of Ecology* 38: 108-113.

Climate

The van Wilgen *et al.* (2004) paper once again tackles the effect that rainfall has on the fire regime. Trollope & Potgieter (1985) has looked at the influence of other climatic variables on fire intensity and demonstrated that there are significant and strong correlations with wind speed and fuel moisture content and fire intensity. Air temperature and relative humidity had no

significant effect. These analyses will be repeated by Govender, *et al.* on a larger database that expands over a longer temporal scale.

Key Publications

van WILGEN, B.W., N. GOVENDER, H.C. BIGGS, D. NTSALA & X.N. FUNDA 2004 (in press).

Manipulating savanna fire regimes to meet conservation objectives: Lessons from a large African national park. *Conservation Biology*.

TROLLOPE, W.S.W & A.L.F. POTGIETER 1985. Fire behaviour in the Kruger National Park. *Journal of Grassland Society South African*. 2: 17-22.

Fire intensity and frequency controls the direct impact on vegetation, which will result in a specific vegetation state.

A large volume of data covering various rainfall regimes, soil substrate, vegetation types, temporal and spatial scales pertaining to the effect that fire frequency and season has on the vegetation type has been collected in the KNP. This is as a result of the long-term (1954 to date) fire experiment in the park. Analysis of this data has been limited. Enslin, *et al.* 2000 and Kennedy, *et al.* 2003, demonstrated that with varying fire frequency and season treatments, there were no significant changes in woody species composition, there were significant changes in the structure of the vegetation and there was more coppice growth on burnt plots than unburnt plots within the *Sclerocarya birrea*/*Acacia nigrescens* and *Colophospermum mopane* vegetation types.

Except for a paper by Trollope & Potgieter (1985) that quantified fire intensity and Trollope *et al.* (1995) that investigated the effect of fire intensity on tree mortality, very little has been done to quantify fire intensity from this experiment. Trollope *et al.* (1995) determined that mortality rate of 7400 trees subjected to head fires ranging from 110kJ/s/m to 6704 kJ/s/m was only 1.3%. Therefore it was concluded that fires alone in the savanna contribute very little to the mortality of trees irrespective of the intensity but the dominant effect of fires is to topkill the trees. The general conclusion was that in the northern savannas of South Africa bush is susceptible to a topkill of stems and branches to a height of approximately 3,5 metres and a minimum fire intensity of 3000 kJ/s/m is necessary to cause a significant topkill of bush to this height.

The numerous exclosures in the park provide an excellent site to separate the effect that herbivory and fire has on the vegetation. The fire frequency within and outside the N'washitsumbe exclosure is very similar. Results presented by Levivk, 2001, showed that there was increase in woody plant cover inside the camp; there was a higher frequency of tall trees (tree >3.99m) and large stem diameter class (>0.16m) inside the camp.

A study was to investigate the response of *Sclerocarya birrea* to fire (Jacobs, 2001). The study concluded that generally, the structure and not the density of marula seedlings were affected by fire. Fire enhanced the change in the structure of marula seedlings to a multi-stemmed morphology, where increasing fire intensities resulted in increased proportions of multi-stemmed individuals. As opposed to the seedlings, adult trees did not respond to fire. Results show the empirical escape height for marulas in the Kruger National Park to be 2.75 m.

Work in progress

- A comprehensive analysis of the effect that fire intensity has on vegetation types in the KNP (Govender *et al.*).
- Prof W. Bond and his colleagues from the University of Cape Town are currently conducting a detailed analysis of the effect that different fire regimes have on the woody vegetation.

- Dr S. Andelman and her colleagues from the National Center are undertaking a similar analysis on the herbaceous layer for Ecological Analysis and Synthesis from Santa Barbara.

Proposed work

- Determine the intensity of fires within and outside exclosures and effects thereafter.
- The analysis of the historical fixed point photographs, taking into account the fire history of the park.

Key Publications

- ENSLIN, B.W., A.L.F. POTGIETER, H.C. BIGGS & R. BIGGS 2000. Long-term effect of fire frequency and season on the woody vegetation dynamics of the *Sclerocarya birrea*/*Acacia nigrescens* savanna of the Kruger National Park. *Koedoe* 43: 27-37.
- JACOBS, O.S. 2001 An autecological study of the Marula (*Sclerocarya birrea*) in the Kruger National Park, with specific reference to the relative impact from elephants and fire. MSc thesis. University of the Witwatersrand.
- KENNEDY, A.D. & A.L.F. POTGIETER 2003. Fire season affects size and architecture of *Colophospermum mopane* in southern African savannas. *Plant Ecology* 167:179-192.
- TROLLOPE, W.S.W., A.L.F. POTGIETER & N. ZAMBATIS 1995. Effect of fire intensity on the mortality and topkill of bush in the Kruger National Park, South Africa. Presented at the *Annual Congress of the Grassland Society of Southern Africa*.

The impact that elephants have on vegetation is controlled by fire intensity and frequency.

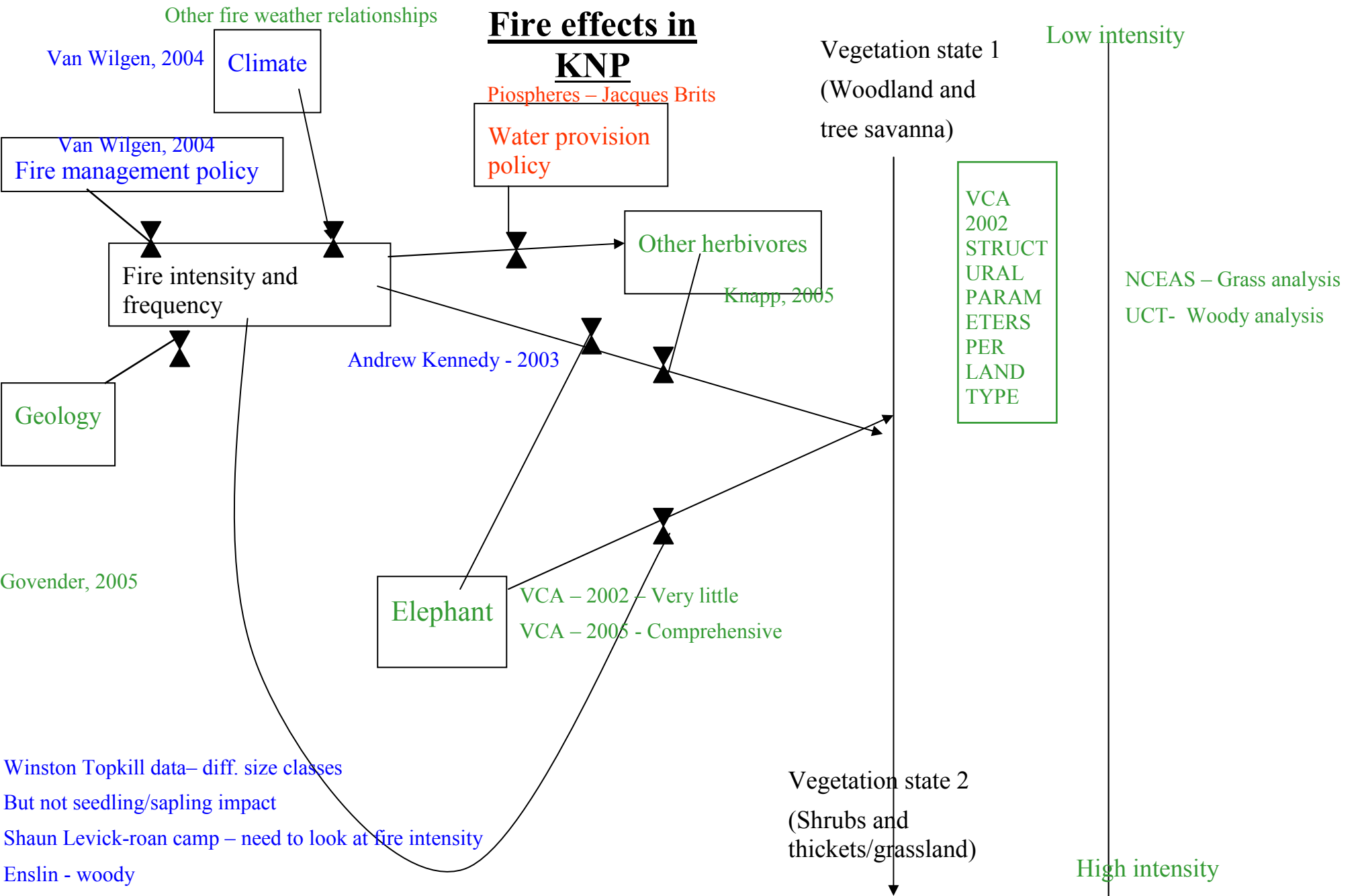
Until recently, no quantified data was available in the KNP, however Trollope *et al.* (1998) subjectively compared changes in the density of large trees between two time periods, using aerial photographs. The paper also included results obtained from comparisons between three exclosures and the area outside. Conclusion from the paper were (1) In the arid landscapes fire alone had significantly less effect on the structure of the woody vegetation than when it was combined with elephants, suggesting that elephants are the major contributing factor in the interaction, (2) Elephant have been primarily responsible for the topkill of trees >3m in height and research in the KNP has shown that trees >3m are generally resistant to fire (Trollope *et al.* 1995).

Work in progress

- Due to various logistic complications the woody data from the 2002 VCA sampling is not available.
- Analysis of the woody data from the 2005 VCA overlaid with the fire history of the park would be an initial step to investigate the fire-elephant interaction at a park scale.

Key Publications

- TROLLOPE, W.S.W., L.A. TROLLOPE, H.C. BIGGS, D PIENAAR & A.L.F. POTGIETER 1998. Long-term changes in the woody vegetation of the Kruger National Park, with special reference to the effects of elephants and fire. *Koedoe* 41: 103-112.



FIRE EFFECTS OVER TIME

LINDSEY GILLSON

Analysis of fossil pollen and charcoal from the Tsavo National Park, Kenya is consistent with the suggestion that at small spatial scales, fire may be important in maintaining grassland areas, but not in creating them (Gillson, 2004). Similar work is underway to establish whether the same relationship holds in the Kruger National Park. The results will be compared with the findings of medium-term (decadal) studies using fixed point and aerial photography, in order to compare and contrast the relationship between fire and tree density at a range of spatial and temporal scales (Gillson and Eckhardt, in prep).

Key Publications

GILLSON, L. (2004) Testing non-equilibrium theories in savannas: 1400 years of vegetation change in Tsavo National Park, Kenya *Ecological Complexity* 1: 281-298

GILLSON, L. & H.E. ECKHARDT (in prep.) Using long-term data for ecosystem management in the Kruger National Park. *Biological Conservation*

FIRE AND ELEPHANT INTERACTIONS IN SOUTHERN AFRICAN SAVANNAS

BROCKETT B.H

Savannas are regarded as event-driven systems (Walker *et al.*1986), and hence disturbances (e.g. fire, drought, floods, elephants and herbivory) are important mechanisms for producing (and maintaining) spatial heterogeneity (Bond & van Wilgen 1996; Schwilk *et al.*1997). The sequence of disturbance events become the drivers necessary to overcome inertia between vegetation states (Mentis & Bailey 1990). Vegetation states can be defined as the horizontal and vertical structure of vegetation as well as its composition (Whelan 1995).

Fire is regarded as a landscape-scale disturbance agent, and many descriptors are used to describe disturbance: frequency, predictability, extent, magnitude, synergism, and timing (Pickett & White 1985; Agee 1993, 1998; Morgan *et al.*2001). Traditionally fire regimes have been described by: intensity, frequency, type of fire, and seasonality (Gill 1975; Trollope 1984). Type of fire is a function of intensity (e.g. flame length) and severity (duration). Currently severity, extent and spatial patterns (Whelan 1995; Brockett 2001; Morgan *et al.*2001), are also considered important. Fire frequency is defined as the mean number of events per time period (Whelan 1995), (2) intensity as energy output per metre of fire front (Trollope 1984; Whelan 1995), and (3) duration is a measure of the effect of fire on the organism or ecosystem (Agee 1993). Post-fire fuel age determines biomass, dead-to-live ratio and fuel continuity (Catchpole 2002). Fire intensity is a function of a number of fuel parameters (e.g. load, continuity, compaction, moisture), and weather conditions, and varies both horizontally and vertically (Whelan 1995), across a landscape. Consequently fire intensity is considered inversely related to frequency. Duration is used as an index of severity, and measured as the variation in peak temperature and duration with height and over space (Whelan 1995). In any fire there is variation in the peak temperature reached, and in the duration of a given temperature (Whelan 1995), and therefore fire severity varies within a fire and spatially across a landscape, and temporally between fires. Weather, topography and fire history interact in complex ways to modify the potential fuel characteristics (notably fuel biomass, and dead-to-live ratio) across landscapes, and for subsequent fires (Whelan 1995; Morgan *et al.* 2001). Rate of spread influences fire intensity, size, and extent burnt. The probability of ignition is a function of land-use, and the propensity for lightning ignited fires, fuel dynamics, annual extent burnt, which together determines fire frequency. Recent post-fire fuels often have poor continuity and insufficient dead fuel to sustain low-to-medium intensity fires (Catchpole 2002). Therefore there is a spatial dependency between landscape events (e.g. fire, rainfall, and herbivory), which influences fire regimes. Relationships between patch characteristics, fire characteristics and landscape dynamics are complex and inter-related. Patch characteristics influence fire characteristics in a complicated cybernetic system. Individual patches and fire events are also linked and affected by external factors such as climate (Binkley *et al.*1993). Consequently fire regimes and vegetation mosaics are temporally and spatially autocorrelated (Morgan *et al.* 2001).

Patchiness occurs at various hierarchical scales (for example at a landscape scale to a plot scale), with fires varying in scale (e.g. low and high severity fires and unburnt islands within fires, to a range of fire size). The effects of these different spatial and temporal fire patterns, are regarded as significant for species conservation (Braithwaite 1987; Andersen 1991; Braithwaite 1996; Parr & Brockett 1999; Brockett 2001; Brockett *et al.* 2001), with the location, size, and juxtaposition of patches in a landscape are important for species survival, colonization, and foraging (Wiens 1976; Binkley *et al.*1993; Forman 1995; Wiens 1997). Hence a small-scale mosaic of burnt and unburnt patches may provide food and cover for seed-eating small mammals which reside along edges of patches or within unburnt islands within larger burnt patches (Binkley *et al.*1993). Hence patchiness (habitat and within-habitat diversity) is a major source of biotic diversity (Huston 1994; Braithwaite 1996; Pickett & Rogers 1997). Huston

(1994) suggests that it is the existence of opportunities, which maintains diversity. For example individual patches support different species or individual species require multiple habitat patch types.

Fire impacts on woody vegetation

Fire impacts woody vegetation by top-killing shrubs, while intense active or passive crown fires can kill older trees (Bailey 1988). Shrubs respond to fire by basal resprouting. Larger trees (> 5 m) can be killed by fire, or respond by basal, aerial resprouting. Responses are species specific. A small proportion of trees respond by basal resprouting (de Ronde *et al.* 2004), which is likely dependent on the severity of the fire. In site of the range of adaptations plants exhibit to fire, only a few species cannot be killed by fire at some point in their life cycle, with physiologically active plants usually being more susceptible to fire than are dormant plants (Bailey 1988). Savanna plant species subjected to fire generally avoid, escape, or endure fire (Bailey 1988). These three responses to fire have been described by Frost (1984) as: avoidance in space, escape in time, and fire tolerance.

Mortality rates of woody plants

Fire induced woody plant mortality rates have been measured by Trapnell (1959) in Zambia, and Rutherford (1981) for *Burkea africana* - *Ochna pulchra* savanna, at Nysvlei Nature Reserve, and by Trollope working in the Kruger National Park (De Ronde *et al.* 2004). Trapnell (1959) showed that mortality rates for early season fires was 7%, whilst late season fires (average for all species) was 17.4%. He also measured mortality rates on unburnt plots and this was 4.2%. Frost (1984) provides a list of the mortality rates for some southern African plants. In the Kruger National Park, Trollope determined the average mortality of 14 of the most common species, subjected to 43 fires ranging in intensity from 110 to 6704 kW/m was 1.3% (De Ronde *et al.* 2004).

Fire intensity is function of fuel loadings, weather conditions, ignition method, and the lighting pattern. The fire behaviour of an intense fire (extreme weather conditions, fully cured and continuous high fuel loadings), using a ring burn, can be described as a passive crown fire. These are fires in which trees discontinuously torch, and where the rate of spread is controlled by the surface fire (Trollope *et al.* 2004). The individual effects of fire on the biota at any selected location depends however on past events and fires, recent fires and future fires. Under high fuel loads and extreme fire weather conditions, and perimeter ring burning, results in high fireline intensities. Top-kill and mortality rates are a function of the height of the woody plant and the fireline intensity. Mortality rates above the flame zone should be lower. The more uniform the terrain the more uniform the fireline intensity. Hence under block burns basalts should have higher fireline intensities than granites (pers. obs.).

Interactions between elephant, fire and other factors

High numbers of elephant (and heavy browsing) result in distorted age-structures of woody plants i.e. either < 1 m, or > 3 m (Dublin 1995). She also found that elephant spend significant amounts of time browsing on seedlings and saplings < 1 m in height, with mature trees being lost at 8%/year from the Masai Mara (Dublin 1995). Trollope *et al.* (1998) subjectively compared large tree densities from aerial photographs for the periods 1940 vs. 1960, and 1960 vs. 1986/89, both inside and outside KNP for four of the major landscapes. Rather than density, woody plant cover should have been used. In addition exclosures in KNP differing in fire frequencies (inside and outside) were used. These authors concluded that fire and elephants significantly reduced bush density. However, a problem with the interpretation is that fire intensities inside and outside the N'waxitshumbe exclosures different (Olivier *pers. comm* 2002), and hence the changes in woody plant cover in this case cannot be attributed to elephants, but rather to differences in fire intensities (inside and outside the exclosure), and

elephant impacts. Prescribed fires inside the enclosure were lit under carefully selected weather conditions (Olivier *pers. comm* 2002), and this problem likely applied to other enclosures used. Bhima & Bredenkamp (1999) conducted a fire 'experiment' in Liwonde National Park, Malawi looking at the regeneration of *Colophospermum mopane* and *Dalbergia melanoxylon*.

Models exploring fire, elephant and other interactions

A significant and seminal work using a modelling and system approach to fire, elephant and other herbivore interactions was by Pellew (1983a, 1983b), working in the Serengeti. Dublin *et al.* (1990) modelled fire and elephant interactions as causes of multiple stable states in the Serengeti-Mara woodlands. Starfield *et al.* (1993) used a frame-based model to explore rainfall, fire and elephant interactions in a *Brachystegia* woodland in Zimbabwe. Baxter & Getz (*in press*) developed a spatial model to explore these interactions.

Baxter & Getz (*in press*) divided the year into two seasons (dry season and wet season). The model assumes that fire intensity is linearly related to grass biomass, with fire weather conditions ignored. No fire spread model was used. A fire in each grid square was assumed to be a uniform random variable drawn on [0,1], and a constant which scales biomass to a fire probability. The woody vegetation is divided into nine stage classes. These are: (1) seedlings < 15 cm ($i = 1$), (2) saplings ($i = 2, \dots, 5$) < 1 m, (3) 1-2 m ($i = 6$), (4) 2-3 m ($i = 7$), (5) 3-5 m ($i = 8$), and (6) > 5 m ($i = 9$). The sapling classes are to prevent seedlings entering the shrub classes within 2 years (individuals advance through the classes subject to sufficient rainfall. The tenth vegetation class records grass biomass. The model assumes that a proportion of trees are top-killed, and that large trees are top-killed. The top-kill rates assumed maximum fireline intensity, with no mortality rate used.

It suggested that the modelling of elephant, fire interactions could be explored using a spatial frame-based model, using a cellular automata fire spread model. The same rainfall seasonality as used by Starfield *et al.* (1993) is suggested. An appropriate grid scale should be used i.e. > 500 m pixels. The location of surface water (e.g. rivers, and artificial waterpoints), and roads, should be included. One of the grid layers of the artificial landscape would describe its vegetation state. A point model would be developed as to the rules (for events) to change vegetation from one state to another (see Starfield *et al.* 1993). Elephant herd locations in the model could be based on a question: It is <season: early winter>, <rainfall: low>, <fire: matches off>, where would elephant herds be according to surface water availability? Then given an area how much time (impacts) would they spend in each vegetation type, until the beginning of the next season when the same question would be asked again, and the elephants may move. Developing and evaluating the results from this model will guide future data collection needs.

References

- AGEE, J.K. 1993. Fire ecology of Pacific Northwest forests. Washinton DC: Island Press.
- AGEE, J.K. 1998. The landscape ecology of western forest fire regimes. *Northwest Science* 72: 24-34.
- ANDERSEN, A.N. 1991. Responses of ground-foraging ant communities to three experimental fire regimes in a savanna forest of tropical Australia. *Biotropica* 23:575-585.
- BAILEY, A.W. 1988. Understanding fire ecology for range management. Pp. 527-557. In: TUELLER, P.T. (ed.). *Vegetation science applications for rangeland analysis and management*. Dordrecht: Kluwer Academic Publishers.
- BAXTER, P.W.J. & W.M. GETZ (*in press*). A model-framed evaluation of elephant effects on tree and fire dynamics in African savannas. *Ecological Applications*.
- BHIMA, R. & G.J. BREDENKAMP 1999. The effect of fire on regeneration of *Colophospermum mopane* and *Dalbergia melanoxylon* and on elephant browsing. *Phytocoenologia* 29(4): 469-484.
- BINKLEY, D., P. BECKER-HEIDMANN, J.S. CLARK, P.J. CRUTZEN, P. FROST, A.M. GILL, A. GRANSTROM, F. MACK, J-C. MENAUT, B. VAN WILGEN & R.W. WEIN. 1993. Group Report: Impacts of fires on ecosystem. Pp. 359-372. In: Crutzen P.J. & J.P. Goldammer. (eds.) *Fire in the Environment: The ecological, atmospheric and climatic importance of vegetation fires*. Environmental Sciences Research Report ES 13. New York: John Wiley and Sons.
- BOND W.J. & B.W. VAN WILGEN. 1996. Fire and plants. London: Chapman and Hall.
- BRAITHWAITE, R.W. 1987. Effects of fire regimes on lizards in the wet-dry tropics of Australia. *Journal of Tropical Ecology* 3:265-275.
- BRAITHWAITE R.W. 1996. Biodiversity and fire in the savanna landscape. Pp. 121-137. In: SOLBRIG, O.T., E. MEDINA & SILVA, J.F. (eds.). *Biodiversity and savanna ecosystem processes*. Berlin: Springer-Verlag.
- BROCKETT, B.H. 2001. Implementing a patch-mosaic burning system in southern African savanna conservation areas. MSc thesis, University of Cape Town, Cape Town.
- BROCKETT, B.H., H.C. BIGGS & B.W. VAN WILGEN. 2001. A patch-mosaic burning system for conservation areas in southern African savanna. *International Journal of Wildland Fire* 10: 169-183.
- CATCHPOLE, W. 2002. Fire properties and burn patterns in heterogeneous landscapes. In: BRADSTOCK, R., J. WILLIAMS, & M. GILL (eds.). *Flammable Australia: the fire regimes and biodiversity of a continent*. Cambridge: Cambridge University Press.
- DE RONDE, C., W.S.W. TROLLOPE, C.J. PARR, B. BROCKETT, C.J. GELDENHUYS 2004. Fire effects on flora and fauna. In: GOLDAMMER, J.G. & C. DE RONDE (eds.) *Wildland Fire Management Handbook for Sub-Saharan Africa*. ???: Global Fire Monitoring Center.
- DUBLIN, H.T., A.R.E. SINCLAIR, & J. McGLADE 1990. Elephants and fire as causes of multiple stable states in the Serengeti-Mara Woodlands. *Journal of Animal Ecology* 59:1147-1164.
- DUBLIN, H.T. 1995. Vegetation dynamics in the Serengeti-Mara ecosystem: the role of elephants, fire and other factors. In: A.R.E. SINCLAIR, & P. ARCESE (eds.) *Serengeti II: dynamics, management and conservation of an ecosystem*. Chicago: The University of Chicago Press.
- FORMAN, R.T.T. 1995. *Land Mosaics*. Cambridge: Cambridge University Press.
- FROST, P.G.H. 1984. The responses and survival of organisms in fire-prone environments. Pp. 273-309 In: BOOYSEN, P. DE V. & N.M. TAINTON (eds.). *Ecological effects of fire in South African Ecosystems*. Berlin: Springer Verlag.
- GILL, A.M. 1975. Fire and the Australian flora: a review. *Australian Forestry* 38:4-25.
- HUSTON, M.A. 1994. *Biological diversity: the coexistence of species in changing landscapes*. New York: Cambridge University Press.
- MENTIS M.T. & A.W. BAILEY. 1990. Changing perceptions of fire management in savanna parks. *Journal of the Grassland Society of Southern Africa* 7:81-84.
- MORGAN, P., C.C. HARDY, T.W. SWETNAM, M.G. ROLLINS, & D.G. LONG. 2001. Mapping fire regimes across time and space: understanding coarse and fine-scale fire patterns. *International Journal of Wildland Fire* 10:329-342.
- PARR C.L. & B.H. BROCKETT. 1999. Patch-mosaic burning: a new paradigm for savanna fire management in protected areas? *Koedoe* 42:117-130.
- PELLEW, R.A. 1983a. The impacts of elephant, giraffe, and fire upon the *Acacia tortilis* woodlands of the Serengeti. *African Journal of Ecology* 21:41-74.

- PELLEW, R.A. 1983b. Modelling and the systems approach to management problems: The Acacia/elephant problem in the Serengeti. Pp. 93-114. In: Owen-Smith, R. (ed.). *Management of large mammals in African conservation areas*. Pretoria: Haum.
- PICKETT, S.T.A. & K.H. ROGERS. 1997. Patch dynamics: the transformation of landscape structure and function. Pp. 110-127. In: BISSONETTE, J.A. (ed.). *Wildlife and Landscape Ecology- Effects of Pattern and Scale*. New York: Springer-Verlag.
- PICKETT, S.T.A., & P.S. WHITE 1985. Patch dynamics and natural disturbance regimes. New York: Academic Press.
- RUTHERFORD, M.C. 1981. Survival, regeneration and leaf biomass changes in woody plants following spring burns in *Burkea africana* - *Ochna pulchra* savanna. *Bothalia* 13, 3 & 4:531-552.
- SCHWIK, D.W., J.E. KEELEY & W.J. BOND 1997. The intermediate disturbance hypothesis does not explain fire and diversity pattern in fynbos. *Plant Ecology* 132: 77-84.
- STARFIELD, A.M., D.H.M. CUMMING, R.D. TAYLOR & M.S. QUADLING. 1993. A frame-based paradigm for dynamic ecosystem models. *AI Applications* 7: 1-13.
- TRAPNELL, C.G. 1959. Ecological results of woodland burning experiments in Northern Rhodesia. *Journal of Ecology* 47:577-588.
- TROLLOPE, W.S.W. 1984. Fire behaviour. Pp. 199-218. In: Booyesen, P. DE V. & N.M. TANTON (eds.). *Ecological Effects of Fire in South African Ecosystems*. Berlin: Springer-Verlag.
- TROLLOPE, W.S.W., L.A. TROLLOPE, H.C. BIGGS, D. PIENAAR, & A.L.F. POTGIETER 1998. Long-term changes in the woody vegetation of the Kruger National Park, with special reference to the effects of elephants and fire. *Koedoe* 41 (2): 103-112.
- TROLLOPE, W.S.W., C. DE RONDE, & C.J. GELDENHUYS. 2004. Fire behaviour. Pp. 27-59. In: J.G. GOLDAMMER, J.G. & C. DE RONDE (eds.) *Wildland Fire Management Handbook for Sub-Saharan Africa*. ???: Global Fire Monitoring Center.
- WALKER B.H., D.A. MATHEWS & P.J. DYE. 1986. Management of grazing systems - existing versus an event-orientated approach. *South African Journal of Science* 82:172.
- WIENS, J.A. 1976. Population responses to patchy environments. *Annual Review of Ecology and Systematics* 7: 81-120.
- WIENS, J.A. 1997. The emerging role of patchiness in Conservation Biology. Pp. 93-107. In: PICKETT, S.T.A., R.O. OSTFELD, M. SHACHAK & G.E. LIKENS (eds.). *The Ecological Basis of Conservation*. London: Chapman and Hall.
- WHELAN, R.J. 1995. The ecology of fire. Cambridge University Press, Cambridge.