Impact of fire frequency on woody community structure and soil nutrients in the Kruger National Park

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Although fire is recognised as an important determinant of the structure and function of South African savannas, there are few studies of long-term impacts. Controlled burning blocks of contrasting fire season and frequency have been maintained throughout the Kruger National Park for almost 50 years. This paper reports on a quantitative study of the Satara plots to determine the long-term impacts of fire frequency on woody community structure and soil nutrients. Increasing fire frequency significantly decreased woody plant basal area, biomass, density, height, and mean stem circumference. The number of stems per plant and the proportion of regenerative stems increased with increasing fire frequency. Effects on species richness of woody plants were inconsistent. There were no significant differences attributable to fire frequency for any of the soil variables except organic matter and magnesium. Organic carbon was highest in the fire exclusion treatment and lowest in soils from plots burnt triennially. Magnesium levels were greatest in the annually burnt soils and least in the triennial plots.

Key words: fire, frequency, Setara, soil nutrients, structure, woody community.

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Introduction

Fire has long been recognised as an essential determinant of the structure and function of African savannas (Trollope 1982; Skarpe 1992; Scholes & Walker 1993). Most work pertaining to fire in southern African savannas has concentrated on fire behaviour (Trollope 1984), herbaceous species composition and productivity (Scott 1984), and the proportion of woody stems killed (Trapnell 1959; Trollope 1980).

Much of the work has focussed on the immediate post-fire period, perhaps up to two years after application of a specified fire treatment. There are relatively few long-term experimental series in the savanna biome, which allow for examination of the long-term impacts of particular fire regimes on woody vegetation and soil nutrients. Comparisons by Trapnell (1959) and Spence & Angus (1971) of areas subjected to different fire frequencies reported that the effect of complete protection from fire was an increase in woody canopy height and biomass. Trapnell's (1959) study opportunistically identified sites of different fire history across a range of environments in Zimbabwe. Spence & Angus' (1971) study reported on plots that had been excluded from fire for only six years. In comparison, controlled burning of experimental blocks of contrasting fire season and frequency in each of the major vegetation types in Kruger National Park (KNP) have been maintained since 1954.

The impact of fire is variable due to a number of factors, including: seasonality, fire intensity, and frequency of burning (Trollope 1982, 1984; Glitzenstein *et al.* 1995). Frequent burning tends to limit the probability of new stems growing through to larger size classes, but will be dependent upon the rate of fuel-load accumulation, which, in turn, is dependent upon rainfall and grazing intensity. The variation in season of burn may change these effects through its influence on fire intensity.

The effects of fire on soil nutrients have been studied largely in the immediate post-fire period (Cass *et al.* 1984), with a few notable exceptions (e.g. Edwards 1961). Results from studies of short-term effects are inconsistent and require more quantitative emphasis to develop predictive capacity (Scholes & Walker 1993).

Within the context of the above, the objective of this work was to assess the long-term effect of increasing fire frequency on woody community structure and soil nutrient status from the long-term experimental plots in the KNP.

Study area

This study was conducted on the controlled fire blocks in the Satara district of the KNP. The area is classified as *Sclerocarya birrea - Acacia nigrescens* savanna by Gertenbach (1983). Woody communities are dominated by *Acacia nigrescens*, *Sclerocarya birrea* and *Pterocarpus rotundifolius*. The shrub layer is dominated by *Dichrostachys cinerea*, *Flueggea virosa* and *Grewia* species. The area is underlain by basalts, giving rise to eutrophic clay soils, with a clay content of 25–50 % (Gertenbach 1983). Mean annual rainfall at Satara is 548 mm.

Methods

Controlled burning of experimental blocks of contrasting fire season and frequency in each of the major vegetation types in KNP have been maintained since 1954. Of interest to this study were four of the treatments of different fire frequency, namely annual, biennial, triennial, and a fire exclusion treatment. In 1983 two additional treatments were added; a four year and a six year rotation. Prior to 1983 the four year rotation treatment blocks had been burnt biennially, and the six year rotation had been burnt triennially.

Fire treatment blocks (6–12 ha) were arranged in a strip and treatments randomly assigned to blocks within the strip. Each strip was approximately across the contour, and hence catenal position was relatively consistent between treatments. Four replicate strips, several kilometres apart, were established per vegetation type. In this study three replicates (Satara, Meraya and Nwanetsi) of the Satara region were assessed. Thus, a total of eighteen fire treatment blocks were sampled during this study (6 treatments x 3 replicate blocks).

The woody vegetation in each block was stratified into two layers; less than 4.5 m high, and greater than 4.5 m high. This was necessary because of the low total biomass, and the low density of large trees in all the treatments except the fire exclusion block. Thus, large individuals would have been undersampled by means of random transects, and if one was included it would have had a disproportionate impact on the resulting mean biomass and associated confidence limits. The two-tier sampling approach described below overcame these problems.

Woody individuals less than 4.5 m were sampled in each block by means of five randomly located transects (50 m x 5 m). Within each transect all woody stems were identified and the basal circumference (at 35 cm above ground level) and height recorded. A visual estimate of the total biomass (%) that was dead was also noted. If a stem taller than 4.5 m was encountered within the transect, it was ignored, except in the fire exclusion treatment blocks.

For all treatments except the fire exclusion, all stems taller than 4.5 m within the entire block were counted, and assessed as dead or alive. At every third stem the basal circumference was measured, and height determined from trigonometric conversion after measurement of the angle to the top of the tree from a known distance away (Shackleton 1993). The density of stems taller than 4.5 m was sufficient in the fire exclusion blocks to sample them by means of the random transects.

Five A-horizon soil samples (2–8 cm deep) were collected systematically from the annual, triennial and fire exclusion blocks. They were analysed in the laboratory for pH (1 M KCl), CEC, Ca, Mg, K, Na (atomic absorption spectroscopy), P (Ambic 1), total N (Keldjahl) and organic carbon (Walkley-Black).

All data were tested for normality and appropriate transformations made where necessary. Basic analysis was via ANOVA with subsequent analysis of residuals. Analyses were performed separately for the two height layers. For significant ANOVAS treatment means were compared further using the Least

Significant Difference (LSD). Biomass was calculated using the allometric equations of Rutherford (1979). Regenerative stems were defined as being $\leq$ 2 cm circumference. This definition includes seedlings as well as new stems resulting from vegetative reproduction.

Results

Biomass

The biomass of stems less than 4.5 m tall was significantly greater in the fire exclusion than in the five fire treatments ($F_{5,\ 84}$ =13.3; $P < 0.0001$) (Table 1). Biomass in the annual, biennial and triennial burn plots was approximately 10 % of that in the fire exclusion. Similarly, the biomass in the taller stratum was also greatest in the fire exclusion treatment ($F_{5,\ 84}$= 2.99; P=0.05). In the taller stratum, there was an increasing biomass with increasing fire frequency except for the six-year burn.

Basal area

Since biomass was calculated from the basal area, the trends in basal area per fire treatment mirrored those for biomass (Table 1). The fire exclusion treatment had a significantly greater basal area than any of the treatments in the low ($F_{5,\ 84}$ =11.96; P <0.0001) and high ($F_{5,\ 84}$ = 8.71; P <0.005) strata. Basal area increased in the low stratum with decreasing fire frequency except for the six-year burn. The reverse applied for the tallest stratum where basal area increased with increasing fire frequency, except for the six-year burn.

Table 1

*Attributes of woody community structure relative to fire frequency (*n *= 15)*

Attribute	Height stratum	Burn frequency(Years)					
		1	2	3	4	6	Exclusion
Biomass (t/ha)	< 4.5 m	0.34 (0.11)	0.27 (0.07)	0.35 (0.08)	1.12 (0.26)	1.09 (0.45)	3.14 (0.49)
	> 4.5 m	4.67 (1.63)	4.25 (1.47)	3.22 (1.72)	1.47 (0.52)	2.89 (1.12)	10.9 (3.55)
Basalarea (m^2/ha)	< 4.5 m	0.52 (0.12)	0.91 (0.17)	1.07 (0.19)	1.44 (0.20)	0.98 (0.22)	2.73 (0.36)
	> 4.5 m	0.62 (0.18)	0.57 (0.16)	0.45 (0.22)	0.25 (0.14)	0.41 (0.10)	2.82 (0.83)
Density (stems/ha)	< 4.5 m	2712 (329)	3480 (582)	3544 (567)	3883 (493)	1960 (294)	2645 (266)
	> 4.5 m	3.0 (0.79)	3.6 (0.73)	3.1 (0.81)	3.3 (0.71)	6.7 (1.29)	138.7 (53.53)
Height (cm)	< 4.5 m	77.2 (5.58)	85.2 (4.79)	83.2 (4.88)	100.3 (6.72)	92.4 (9.78)	115.0 (5.63)
Circumference (cm)	< 4.5 m	4.04 (0.37)	4.63 (0.28)	4.85 (0.25)	5.63 (0.36)	5.97 (0.60)	8.13 (0.79)
No. stems/ plant	< 4.5 m	5.3 (0.87)	4.0 (0.62)	3.5 (0.23)	4.0 (0.31)	2.8 (0.28)	2.7 (0.22)
No. species /transect	< 4.5 m	4.9 (0.51)	5.6 (0.38)	6.8 (0.50)	6.3 (0.41)	5.0 (0.47)	6.7 (0.40)

Density

There were significant differences in density of stems in both height strata; < 4.5 m ($F_{5,84} = 2.66$; $P < 0.05$) and > 4.5 m ($F_{5,84} = 6.38$; $P < 0.005$) (Table 1). In the lower stratum density increased with decreasing fire frequency until dropping off with the two lowest frequencies, i.e. the six-year burn and fire exclusion. For the taller stratum, there was a slight trend for increasing density with decreasing fire frequency, although not consistent. Analysis of LSDs indicated that for the larger stems the fire exclusion treatment had a significantly greater density than any of the burned treatments, between which there were no significant differences.

Height

There was a significant trend of increasing mean height with decreasing fire frequency ($F_{5,84} = 4.5$; $P < 0.001$) (Table 1). The annual burn had the shortest stems on average (77.2 ± 5.6 cm), whilst the fire exclusion had the tallest (115.0 ± 5.6 cm).

Number of stems/plant

The greatest number of stems per plant was evident in plots subjected to annual burning (Table 1), and the least in the fire exclusion treatment, which had almost half the stems per plant relative to those burnt annually. Overall there was a significant decrease in stems per plant with decreasing fire frequency ($F_{5,84} = 3.72$; $P < 0.005$).

Number of species per transect

Although there were significant differences in the number of species per transect ($F_{5,84} = 3.57$; $P < 0.01$) there was no clear relationship relative to fire frequency (Table 1). The fire exclusion treatment, four-year, three-year and two-year burns had significantly more species than either the six-year and one-year burns which were not significantly different from one another.

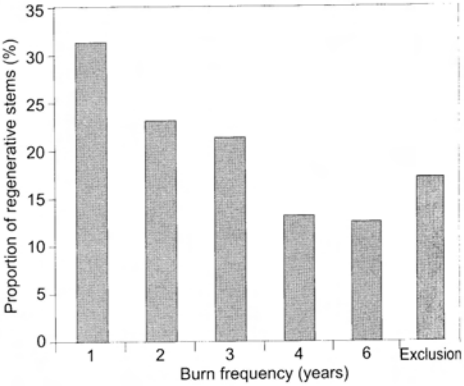

Fig. 1. Proportion of regenerative stems (≤ 2 cm circumference) across a range of fire frequencies.

Proportion of regenerative stems

A significantly higher proportion of regenerative stems was recorded in the annual burn treatment (31.4 ± 4.1 %) than any of the other treatments or fire exclusion plot ($F_{5,84} = 5.29$; $P < 0.001$). There was a marked decrease in the proportion of regenerative stems with decreasing fire frequency, except for the fire exclusion treatment, which was higher than the four and six-year burn frequency (Fig.1).

Soils

Analysis of the soil variables revealed that only in the case of organic carbon ($F_{2,42} = 3.31$; $P < 0.05$) and magnesium ($F_{2,42} = 4.15$; $P < 0.05$) did a significant difference exist between areas subjected to differing fire frequencies. Organic carbon was highest in the fire exclusion treatment (2.2 ± 0.14 %) and least in soils from the triennial burn frequency (1.9 ± 0.15 %). Magnesium was greatest in the annually burnt soils (776 ± 91 mg/kg), and least in the triennial plots (597 ± 60 mg/kg). The fire exclusion was intermediate between these two.

Discussion

Increasing fire frequency had a clear effect on several attributes of woody community structure. Basal area, biomass, density, height, and mean stem circumference all decreased with increasing fire frequency, and overall woodiness was highest in areas protected from fire. A similar trend has been reported by other researchers (Trapnell 1959; Spence & Angus 1971; Trollope 1982). The number of stems per plant and proportion of regenerative stems increased with increasing fire frequency, as also reported by San Jose & Farinas (1983) and Scholes & Walker (1993). Not only do the number of regenerative stems increase with fire frequency, but survival of seedlings is greater in recently burnt areas relative to unburnt sites (Khan & Tripathi 1989). However, trends in the number of stems per plant is species specific (Tchie & Gakahu 1989), and for the period immediately after the fire is related to fire intensity (Canadell *et al*. 1991). The effects of fire intensity with respect to the number of shoots per plant decreases in time.

In summarising other studies, Trollope (1982) concluded that fire frequency had little effect on density of stems over a long period (15 years). Strang (1974) also found woody density to be unaffected by regular burning after comparison of two paired sites (fire break versus fire protected area). Our results contradict these findings. In the lower height category (< 4.5 m) density decreased with increasing fire frequency, although the density of all treatments was of the same order of magnitude, except for the six-year burn frequency. In the taller height category (> 4.5 m) the density of stems was approximately 40 times greater in the exclusion plots than the fire treatments. Conversion of these data to plant basal area or biomass multiplies this difference because of the greater role of large trees in ecosystem processes. Additionally, although the density of stems in the different treatments was of the same order of magnitude, the size of stems (circumference and height) in the fire exclusion plots was significantly larger. Thus, perhaps density of stems is an inadequate index of fire impact, and 15 years is too short a period to contrast fire treatments. Increasing fire frequency results in woody communities dominated by thinner and shorter stems, at the same or higher densities (this study) or lower densities (Strang 1974). If stem densities do not decrease, or only marginally, it can be anticipated that relative woody productivity will increase with increasing fire intensity because small stems are characterised by higher growth rates (Shackleton 1997). Net production per unit area will be lowered because of the greatly reduced total woody biomass. Additionally, this study indicated an increasing biomass of large stems with increasing fire frequency, other than the exclusion treatment. This suggests that the few trees that succeed in growing sufficiently tall to be relatively immune to the effects of fire, benefit from reduced competition from the reduced understory layers.

Investigations of the effects of fire frequency on soil chemistry have yielded variable results (Scholes & Walker 1993). This study found few significant effects of fire frequency on soil chemistry, except for organic carbon and magnesium. Organic carbon was not significantly different between differing fire frequencies, but was significantly higher in the fire exclusion treatment. The absolute difference between the fire exclusion areas and the fire frequency with the lowest organic carbon was small (0.3 %), representing a relative decrease of 14 % over more than four decades. In contrast, Trapnell (1959) reported an equivalent increase in soil carbon in areas burnt annually relative to unburnt areas. Scholes & Walker (1993) suggested that whether or not organic carbon increased or decreased under contrasting fire frequencies was dependent on fire intensity, soil type and changes in primary production resulting from the effects of fire, and required more attention to provide some predictive capacity in this regard. Magnesium levels were highest under annual burning, but there was no clear trend relative to decreasing fire frequency. Previous work suggest that soil cations are rarely effected by fire frequency (Scholes & Walker 1993). The absence of differences recorded here support this conclusion. Where effects have been recorded, trends are inconsistent, depending upon vegetation type, soil type, climate and fire behaviour (Cass *et al.* 1984), and may be a result of differential ash deposition.

This study found no differences in soil nitrogen. Jones *et al.* (1990) analysed soil from one of the three sites (Nwanetsi) sampled in this study. They found a trend of decreasing total nitrogen with increasing fire frequency, but without replication were unable to determine statistical significance. Their results for organic carbon were similar to those of this study. Given that the C:N ratio of soils falls within a narrow range (Scholes & Scholes 1997) it is anomalous that the change in soil carbon was not associated with a change in total nitrogen.

One problem in attempting to determine the effects of fire on vegetation is that the direct fire impacts cannot always be isolated from the effects of post-fire management (Van Wyk 1971; Trollope 1982, 1984). For example, burnt areas are attractive to a variety of herbivores (Moe *et al.* 1990; Shackleton 1992). Thus, there may be a period of intense grazing and browsing on new regrowth following a fire, the effects of which are inversely related to the size of the burnt area. Hence, what are the impacts of this relative to the impacts of the fire, and what impacts are a result of both events in succession? Herbivore impact can be diluted if sufficiently large areas are burnt relative to the density of herbivores. If not, any contrasts of fire frequency cannot be isolated from the simultaneous effects of herbivores, which if at high densities will probably serve to reduce woody biomass (Strang 1974). The effects of herbivory also interact with fire frequency and intensity because grazing reduces the rate of fuel-load accumulation, thus reducing fire intensity and possibly frequency, but at the same time maintains the new coppice growth at a height that is susceptible to a repeat fire (Trollope 1982; Sweet & Mphinyane 1986). Overgrazing of the fire plots is considered an important confounding variable in the Kruger National Park experimental plots (Van Wyk 1971).

In conclusion, although the confounding effects of increased grazing on the experimental burn plots needs to be considered, it appears that different fire frequencies have a marked effect on several attributes of the structure of woody communities in semi-arid savannas, on basalt derived soils.

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