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The effect of fire history on soil nutrients and soil organic carbon in a semi-arid savanna woodland, central Namibia

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Fire is an integral part of savanna ecosystems that has shaped these systems since the Miocene. Substantial uncertainty about fire effects in semi-arid ecosystems exists. Fire may affect ecosystem productivity directly through nutrient volatilisation, increased mineralisation and altering organic matter quantity, and indirectly through altering vegetation structure. We explored the effects of fire history and vegetation patch types (tree canopy vs inter-canopy) on soil nutrients and soil organic carbon (SOC) in a semi-arid ecosystem. We collected soil samples along transects in four treatments with different fire histories (1 to 24 years since the last burn). In the statistical analyses, tree canopy and inter-canopy samples along transects were differentiated. Fire showed an inconsistent effect on soil nutrients and SOC. There was a short-term negative influence on total nitrogen, whereas phosphorus, potassium and magnesium increased in the 1-year treatment. Sodium consistently decreased with increasing time since the last burn, whereas SOC and calcium were not affected. Calcium and magnesium were significantly higher under canopy relative to inter-canopy patches. There was no significant interactive effect between fire history and vegetation patch type on soil nutrients and SOC. Management decisions regarding fire within the frequency experienced in this system appear not to necessitate concern regarding soil resource impacts.

Keywords: cations, fire intervals, fire treatment, sandy soils, time since last burn, vegetation patch types

Introduction

Soils are important reserves of carbon and nutrients in the biosphere (Neary et al. 2005), and the cycling of these nutrients is influenced by fire in many ecosystems (Holt and Coventry 1990). Soil nutrients and carbon:nutrient ratios play significant roles in regulating the productivity of terrestrial ecosystems and soil organic carbon (SOC) pools (Parton et al. 1987; Vitousek and Howarth 1991). Savannas are inherently heterogeneous, with vegetation cover composed of a matrix of grasses and bare ground interspersed with woody plants (Scholes and Walker 1993; Scholes and Archer 1997). This heterogeneity in plant cover can drive spatial heterogeneity in soils as plant cover can influence pools of soil nutrients and SOC (Belsky et al. 1989; Belsky 1994; Ludwig et al. 2004). Concentrations of soil nutrients and SOC can be substantially higher under tree canopies as compared with inter-canopy areas in savannas (Campbell et al. 1988; Scholes and Walker 1993) and this may be exacerbated by deposition of urine and dung if animals preferentially spend time under canopies (Sitters et al. 2017). Variations in the distribution of soil nutrients and SOC between these 'vegetation patch types' may be a function of nitrogen fixation, high litter quantity or quality, subcanopy accumulation of materials transported by erosional processes, microclimate modification (e.g. moisture and temperature), and subsequent changes in decomposition rates and microbial community composition (Belsky et al. 1989, 1993; Throop and Archer 2007).

Many ecosystems, in particular, savannas, grasslands and Mediterranean ecosystems, are fire-prone, with fire occurring from both natural and anthropogenic ignition (Trollope 2007). Savannas are characterised by a grassy understory which, in combination with an extended dry season, makes them extremely flammable much of the year (Scholes and Hall 1996). Frequent fire may have long-term detrimental effects on productivity as a result of nutrient losses (e.g. N and P volatilisation) and nutrient redistribution via the translocation downward in the soil profile during fire (Kauffman et al. 1992; DeBano 2000). Vegetation patch types can potentially interact with fire by regulating the intensity of fire through affecting grass biomass (fuel) and moisture content (Higgins et al. 2000; Holdo 2005). A key question is what are the independent and interactive effects of fire and vegetation patch types on soil nutrients and SOC in woodland savannas? This is especially relevant given that fire is an active agent of nutrient cycling (Holt and Coventry 1990) and an important determinant of tree canopy cover in these ecosystems.

Previous studies have explored fire effects on soil nutrients (mainly nitrogen [N] and to a lesser extent phosphorus [P], potassium [K], magnesium [Mg], calcium

[Ca] and sodium [Na]) and carbon (C) dynamics in savanna ecosystems (Cook 1994; Ojima et al. 1994; Ross et al. 1997; Neff et al. 2005; Ansley et al. 2006; Castaldi et al. 2010; Hurteau and Brooks 2011; Novara et al. 2013; Molla et al. 2014). However, fire effects on soils vary greatly amongst savannas based on soil nutrient availability (Khavhagali 2008; Holdo et al. 2012). In addition, this variability may also be a function of other factors such as fire intensity, fire severity, type of burned vegetation, distribution of fuel on the soil surface and regional climate (Certini 2005; Novara et al. 2013). Many of these factors vary over time and landscape space (Neary et al. 2005). Some studies reported a decline in SOC following the combustion of organic matter in savanna soils (Fynn et al. 2003; Knicker 2007), whereas others report no change in SOC content after fire (Kavdir et al. 2005). In a study conducted in nutrient-poor Australian savannas, Cook (1994) reported increased nutrient availability (P, K, Ca, and Mg) and a high N loss due to volatilisation. In another nutrient-poor savanna ecosystem, a decline in soil organic matter with frequent burning was associated with increased mineralisation of organic matter and decreased microbial activities (Aranibar et al. 2003; Mills and Fey 2005).

Recent studies have considered the interactive effects of fire and vegetation patch types on soil nutrients and SOC content in both nutrient-poor and -rich soils in semi-arid ecosystems (Khavhagali 2008; Coetsee et al. 2010; Holdo et al. 2012). In the Kruger National Park, a nutrient-poor semi-arid savanna ecosystem, there was no effect of fire on soil nutrients and SOC content. However, there were strong positive effects of tree canopies on soil nutrients and SOC content (Khavhagali 2008; Coetsee et al. 2010; Holdo et al. 2012). Generally, fire reduces tree canopy cover in these ecosystems, thus fire may affect nutrients and C content in soils indirectly by altering vegetation structure (Khavhagali 2008; Coetsee et al. 2010; Holdo et al. 2012). The expansion on these earlier studies, but in a savanna with denser woody coverage, would improve our understanding of the effects of fire on soils, because there is a critical knowledge gap on fire effects on soils in semi-arid woodland savannas. This is especially the case in Namibia. Fire studies in Namibian woodland savannas have been limited to investigating certain aspects such as the effect of fire frequency (Sheuyange et al. 2005), the role of fire in preventing bush thickening (Joubert et al. 2012), and the assessment of fire frequency, fire seasonality and fire intensity within the Okavango region (Stellmes et al. 2013). A critical gap in our understanding of the effects of fire remains, in that we have limited understanding of responses of SOC and soil nutrients in semi-arid woodland savanna ecosystems.

Here, we used management units with different fire treatments (time since last burn ranging from 1 to 24 years and fire interval ranging 6.2 to 18.5 years) in a semi-arid woodland savanna to determine the independent and interactive effects of fire and vegetation patch types on soil nutrients and SOC. This is an important step for a better comprehension of the dynamics of SOC and soil nutrients in semi-arid woodland savanna ecosystems in response to ecosystem disturbances such as fire, to promote land management practices that may improve site productivity (Concilio et al. 2006). In this study, we aimed to determine how soil nutrients and SOC are affected by (1) time since last burn and (2) vegetation patch type in four different fire treatments (Table 1). This study improves the current knowledge and understanding of fire effects on SOC and soil nutrients in arid and semi-arid woodland savanna ecosystems.

Study area

The study was conducted in the arid end of the woodland savanna biome (Giess 1971) in Waterberg Plateau Park (WPP), north central Namibia (between 20°37′ S, 17°08′ E and 20°11′ S, 17°26′ E) at 1 650 m above sea level (Figure 1). The sandstone plateau is 50 km in length and 16 km in width, and it is up to 200 m higher in elevation than the surrounding plain (Schneider 1993). The 45 000 ha park was established in 1972 for breeding and maintaining populations of rare and endangered mammal species, e.g. black rhino (*Diceros bicornis*), white rhino (*Ceratotherium simum*), African buffalo (*Syncerus caffer*), sable antelope (*Hippotragus niger*), tsessebe (*Damaliscus lunatus*) and roan antelope (*Hippotragus equinus*) (Schneider 1993). The solidified dunes that form the top of the plateau belong to the Etjo formation, which forms part of the Karoo sequence (Pickford 1995). The sandstone is covered by brownish to light grey, medium-grained aeolian sand from the Kalahari Basin (Erb 1993). The sandy soil is nutrient poor with relatively low clay content (≤3.7%) and pH ranging from 3.6 to 6.0 (Erb 1993; Erckie 2007). The vegetation is classified as tree savanna and Kalahari woodland (Giess 1971). The woodland overstorey is mostly dominated by *Terminalia sericea*, *Burkea africana*, *Ochna pulchra* and *Combretum* spp. (Giess 1971). The understorey consists of grass species such as *Eragrostis pallens*, *Brachiaria nigropedata* and *Digitaria seriata*. The climate is strongly seasonal (Erckie 2007). Mean annual rainfall is 450.2 ± 75.4 mm (Mukaru 2009). Rain falls predominantly in summer; 90% of this summer rain occurs between October and March (Erb 1993). Potential annual evaporation ranges between 2 800–3 000 mm (Erb 1993). The daily minimum temperature for winter months ranges between 4 °C and 5 °C but during June, the temperatures can go as low as −5 °C (SASSCAL WeatherNet 2014; http://www.sasscalweathernet.org/). In summer, the daily minimum temperature is 9–13 °C and the daily maximum temperature is 31–39.4 °C (Erckie 2007).

Materials and methods

Field sampling

We used a space-for-time substitution design where we analysed temporal trends from a series of different-aged

Table 1: Fire history (time since last burn and mean fire return interval) of the four different fire treatments used to investigate soil nutrients and soil organic carbon at Waterberg Plateau Park

Fire treatment	Years since last burn	Mean fire interval (y)
1	1	6.2
2	2	9.3
3	14	9.3
4	24	18.5

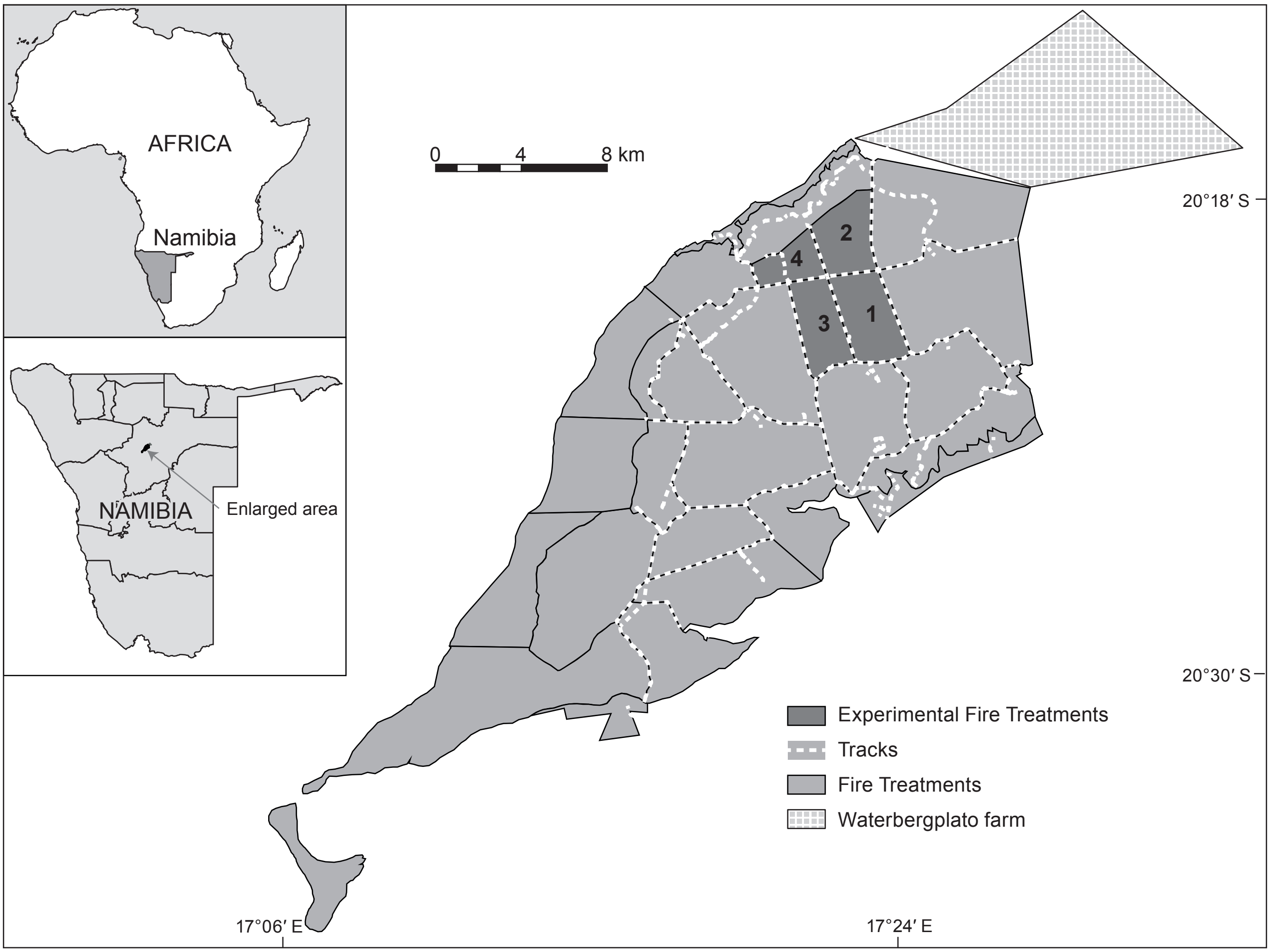

Figure 1: Location of Waterberg Plateau Park in Namibia and map of the park showing the fire treatments where the field experiment was conducted. The years since last burn and mean fire interval of the four fire treatments are listed in Table 1

sites (Pickett 1989). We worked in four fire treatments that differed in years since the last burn (Table 1). In each fire treatment, we established six transects (200 m each) and collected soil samples (10 cm depth × 7.7 cm width) every 40 m using a soil auger (N = 5 soil samples per transect × 6 transects per treatment × 4 fire treatments = 120 soil samples). Some samples were collected under tree canopies (tree canopy = 57 samples), whereas some were collected in open space away from tree canopies (inter-canopy = 63 samples) based on where the 40 m point fell on the transect. Inter-canopy was defined as any sampling point that was at least 0.5 m from the canopy edge dripline. Litter was brushed away from the soil surface prior to sampling. Sampling took place from February to April 2014.

Laboratory methods

Soils were air dried and passed through a 2 mm sieve prior to chemical analyses. Soil organic carbon was determined using the colorimetric Walkley–Black method (Lettens et al. 2007), using potassium dichromate ($K_2Cr_2O_7$) and concentrated sulphuric acid (H_2SO_4). Absorbance was measured at 600 nm using a UV/VIS spectrophotometer (model 916; GBC Scientific Equipment, Melbourne, Australia), with a calibration curve based on glucose. Total N was determined with combustion analysis using a CHN elemental analyser (LECO Corporation, St Joseph, MI, USA). Available P was extracted using Olsen's procedure (Olsen et al. 1954). The absorbance was measured at 882 nm using a UV/VIS spectrophotometer (Model 916; GBC Scientific Equipment). Soil texture was determined with the pipette method (Gee and Bauder 1986) using sodium hexametaphosphate, water and sodium carbonate as dispersing agents. Cations (K, Ca, Mg and Na) were extracted using ammonium acetate (1.0 M, pH 7, 1:20 [v/v] soil:extractant ratio, 30 min extraction). The absorbance was read at different wavelengths for different elements (K = 766.490 nm, Ca = 315.887, Mg = 279.079 and Na = 589.592 nm), using inductively coupled plasma optical emission spectrometry (ICP-OES; Thermo Fisher Scientific, Cambridge, UK). All analyses were conducted at the Soil Laboratory of the Ministry of Agriculture, Water and Forestry, Namibia.

Statistical analysis

Response variables were assessed for conformity to assumptions of normality and homogeneity of variance. We used log and logit transformations, as appropriate for individual variables, to improve normality and homogeneity of variance. We used two-way analysis of variance (ANOVA) to assess whether the response variables (soil nutrients and SOC) differed among fire treatments, between vegetation patch types, or if there were interactive effects between fire treatments and vegetation patch types. For significant main effects and interactions, we assessed among-group difference using *post-hoc* Tukey's multiple comparison tests (Tukey correction). The effects were considered to be significant at probability less than 0.05. Statistical analyses were done in R 3.5.1 (R Core Team 2018).

Results

A comparison of SOC and soil nutrients among fire treatments showed an inconsistent effect, with generally lower soil nutrients in the 2 and 24 years since last burn treatments than the 1 and 14 years since last burn treatments. Mean SOC ranged from 0.32% to 0.39% C by mass. There was a significant main effect of fire treatment on SOC content ($p < 0.05$; Table 2), although no groups were significantly different from each other (Table 3). The SOC did not differ between vegetation patch types and there was also no significant interaction between fire and vegetation patch type on SOC (Table 2). Total N content ranged from 0.06% to 0.14% by mass. There was a significant main effect of fire treatment on total N ($p < 0.05$; Table 2), with the 14 years fire treatment having high total N relative to other fire treatments (Table 3). Total N did not differ between vegetation patch types and there was also no significant interaction between fire and vegetation patch type on Total N (Table 2). Phosphorus ranged from 0.38 to 1.7 ppm. There was a significant main effect of fire treatments on P ($p < 0.05$; Table 2), with the 14 years fire treatment having high P, whereas the 2 year fire treatment had the lowest P relative to other fire treatments (Table 3). Phosphorus did not differ between vegetation patch types and there was also no significant interaction between fire and vegetation patch type on P (Table 2).

Potassium concentrations ranged from 20 to 47 ppm. There was a significant main effect of fire treatments on K ($p < 0.05$; Table 2); fire treatments that burned 1 and 14 years ago had high K relative to those that burned 2 and 24 years ago (Table 3). Potassium did not differ between vegetation patch types and there was also no significant interaction between fire and vegetation patch type on K (Table 2). Sodium ranged from 0 to 32 ppm. There was a significant main effect of fire treatments on Na ($p < 0.05$; Table 2); Na decreased sharply with increasing time since last burn (Table 3). There were no significant effects between vegetation patch types nor was there a significant interaction effect between fire and vegetation patch type on Na (Table 2). Magnesium ranged from 14 to 28 ppm. There was a significant main effect of fire treatments on Mg ($p < 0.05$; Table 2); the fire treatment that burned 2 years ago had low Mg relative to other fire treatments (Table 3). There was also a significant main effect of vegetation patch types on Mg ($p < 0.05$; Table 2); Mg was significantly higher under tree canopy relative to inter-canopy patches (Table 4). There was no significant interaction effect between fire and vegetation patch type on Mg (Table 2). Calcium ranged from 43 to 66 ppm. There was no significant main effect of fire treatments on Ca, but there was a significant main effect of vegetation patch types on Ca (Table 2), Ca was significantly higher under tree canopy relative to inter-canopy (Table 4). There was no interaction effect between fire and vegetation patch types on Ca (Table 3). Soil texture differed among fire treatments, with clay content being significantly lower, whereas silt was high in the fire treatment that was burned

Table 2: *F*-ratio and the level of two-way ANOVA assessing the effects of time since last burn (year), vegetation patch types (tree canopy and inter-canopy), and their interaction on soil organic carbon (SOC) and nutrient concentrations of the surface soil (0–10 cm) in a semi-arid savanna, Namibia

Parameter	Effect		
	Time since last burn (Time)	Vegetation (Veg)	Time × Veg
SOC (%)	2.883 *	0.398	0.179
Total N (%)	17.73 ***	0.303	0.096
P (ppm)	26.97 ***	0.634	2.400
K (ppm)	15.35 ***	0.433	0.358
Na (ppm)	36.86 ***	0.731	2.602
Mg (ppm)	3.290 *	9.305**	0.602
Ca (ppm)	1.573	3.470*	0.267

* $p < 0.05$, *** $p < 0.001$

Table 3: Mean (±SE) soil organic carbon (SOC) and nutrient concentrations in the surface soil (0–10 cm) in fire treatments with different years of time since last burn in a semi-arid savanna, Namibia. For each fire treatment, n = 6. Different superscript letters following means within a row differ significantly ($p < 0.05$), based on a *post-hoc* Tukey test

Parameter	Time since last burn (years)			
	1	2	14	24
SOC (%)	0.39 ± 0.03^{a}	0.32 ± 0.02^{a}	0.39 ± 0.02^{a}	0.35 ± 0.02^{a}
Total N (%)	0.07 ± 0.01^{a}	0.08 ± 0.01^{a}	0.13 ± 0.01^{b}	0.05 ± 0.01^{a}
P (ppm)	1.44 ± 1.87^{bc}	0.38 ± 0.03^{a}	1.67 ± 0.17^{c}	1.25 ± 0.22^{b}
K (ppm)	42.6 ± 4.86^{a}	22.8 ± 3.64^{b}	38.9 ± 3.07^{a}	21.7 ± 1.40^{b}
Na (ppm)	30.5 ± 3.55^{c}	22.8 ± 5.44^{b}	9.30 ± 2.62^{b}	0.13 ± 0.13^{a}
Mg (ppm)	27.6 ± 4.81^{b}	14.3 ± 2.32^{a}	20.4 ± 2.98^{ab}	18.7 ± 1.79^{ab}
Ca (ppm)	60.0 ± 11.2^{a}	66.3 ± 12.1^{a}	42.0 ± 46.6^{a}	51.1 ± 7.88^{a}

Table 4: Mean (±SE) nutrient concentrations in the surface soil (0–10 cm) under different vegetation patch types (tree canopy and inter-canopy) in a semi-arid savanna, Namibia. Different superscript letters following means within a row differ significantly ($p < 0.05$) based on a *post-hoc* Tukey test. SOC = soil organic carbon

Parameter	Vegetation patch type	
	Tree canopy	Inter-canopy
SOC (%)	0.37 ± 0.02^{a}	0.36 ± 0.01^{a}
Total N (%)	0.08 ± 0.01^{a}	0.09 ± 0.01^{a}
P (ppm)	1.15 ± 0.13^{a}	1.20 ± 0.14^{a}
K (ppm)	33.4 ± 3.05^{a}	29.2 ± 2.24^{a}
Na (ppm)	15.9 ± 2.82^{a}	14.8 ± 2.97^{a}
Mg (ppm)	24.9 ± 2.73^{a}	15.3 ± 1.46^{b}
Ca (ppm)	65.9 ± 8.41^{a}	44.1 ± 4.60^{b}

2 years ago relative to other fire treatments (Table 5). There was no significant difference in soil texture between vegetation patch types (Table 6).

Discussion

Fire is an integral part of the ecosystem, and has a substantial impact on soil nutrients; however, there is controversy over the impact of fire on soil nutrient concentrations (Mills and Fey 2003). Generally, in the absence of fire, vegetation is either consumed by herbivores or returns to the soil surface as organic matter and is decomposed by soil microbial organisms over time (Mills and Fey 2003). In contrast, in the presence of fire, nutrients that are bound in organic matter are released as ash onto the soil surface (Mills and Fey 2003). However, these nutrients may or may not be reincorporated into the soil; the fate of these nutrients depends on several factors such as the soil texture and the post-fire climatic conditions (Mills and Fey 2003).

Soil organic carbon

There was a significant main effect of fire treatments on SOC content, although no groups were significantly different from each other. The result supports earlier work that reported no significant change in SOC content after fire (Kavdir et al. 2005; Khavhagali 2008; Coetsee et al. 2010; Holdo et al. 2012) in similar nutrient-poor South African savannas. Generally, nutrient-poor savannas have a low amount of organic matter that is distributed fairly uniformly. Low amounts of organic matter may lead to low-intensity fires in which there is limited volatilisation of SOC from soils during the fire (Certini 2005). Loss of SOC may also be restricted if fires are not hot enough to cause woody mortality or to affect soil organisms (Neary et al. 1999). It may also be that soils may simply have had insignificant change in SOC content after fire to be discernible due to low levels of SOC in nutrient-poor savanna systems prior to burns. Alternatively, it could be that there is some SOC volatilisation with fire but this is counteracted by increased plant productivity and subsequent inputs to SOC pools (Schuman et al. 2002). The SOC loss from burning often increases with long-term exposure to repeated fire (Pellegrini et al. 2018), so it may be that SOC patterns would change at this site with long-term management. These results suggest that, although fire management practices can substantially alter SOC (Schuman et al. 2002), low-nutrient systems such as WPP may be relatively unresponsive to fire management.

We observed no significant difference in SOC between tree canopy and inter-canopy patches. This contrasts the well-known phenomenon that nutrients increase under tree canopies relative to inter-canopies (Belsky et al. 1989, 1993; Scholes and Walker 1993; Khavhagali 2008; Coetsee et al. 2010; Holdo et al. 2012). This lack of vegetation patch difference in SOC may be a function of the contrasts in vegetation structure between WPP and other study sites. Firstly, soils in our study site are sandy, hence there is generally low organic matter accumulation in these soils due to physicochemical limitations (Schimel et al. 1994; Schmidt et al. 2011). Secondly, the spatial pattern of canopies and our sampling locations may have influenced the lack of vegetation patch effect on SOC. There is relatively little separation among tree canopies in the areas where fire has not occurred recently (e.g. 14 and 24 y since fire), with the vegetation structure of an open woodland. Nonetheless, there were always adequate inter-canopy locations that met our sampling criteria of being at least 0.5 m from a tree canopy dripline. This structure of relatively frequently spaced tree canopies may lead to more uniform distribution of root and aboveground litter inputs to soils, both in the inter-canopy and below canopies, than occurs in many savanna systems. In contrast, there were very distinct, more widely separated tree canopies in the recently burned areas (e.g. 1 and 2 y since fire) and SOC was still not affected by vegetation patch type in these areas. Given that these were largely re-growth from trees that were not killed from the fire, it may be that roots and belowground influences persist from the pre-burn plant community. Thirdly, we did not separate out woody patches by age (e.g. 'old' trees that existed before fire, regrowth of old trees post-fire, or 'young' trees that established post-fire), thus there is potentially a lot of variation in woody plant age both within and among fire treatments. This might affect soil nutrients due to the strong influence of woody plant age on soil spatial patterns (Throop and Archer 2008).

Total nitrogen

Although we did not find a consistent pattern between nutrients and time since last fire, we observed a negative short-term influence of fire on total N in the 1 year burned treatment. This result is compatible with previous work in chaparral soils, where it has been suggested that 50% of N in the top 20 mm volatilises even in low-intensity fire regimes and N losses may exceed N inputs (DeBano et al. 1979). Similarly, this result is supported by Cook (1994) who reported increased nutrient availability of P, K, Ca and Mg but high N loss due to volatilisation after fire in a nutrient-poor Australian savanna.

Similarly to SOC, we observed no significant difference in total N between tree canopy and inter-canopy patches.

Table 5: Soil texture for soils in different management units at the Waterberg Plateau Park that differed in the number of years since the last burn. Within a particle size, means with different superscript differ significantly ($p < 0.05$), based on a *post-hoc* Tukey test

Time since last burn (year)	Sand content (%)	Clay content (%)	Silt content (%)
1	94.9 ± 0.20^a	3.41 ± 0.13^a	1.66 ± 0.18^a
2	94.4 ± 0.18^a	2.95 ± 0.17^b	2.66 ± 0.21^b
14	94.7 ± 0.39^a	3.69 ± 0.16^a	1.61 ± 0.39^a
24	94.9 ± 0.18^a	3.45 ± 0.13^a	1.68 ± 0.12^a

Table 6: Soil texture for soils in different management units at the Waterberg Plateau Park that differed between vegetation patch types

Vegetation patch type	Sand content (%)	Clay content (%)	Silt content (%)
Tree canopy	94.9 ± 0.14	3.31 ± 0.12	1.76 ± 0.13
Inter-canopy	94.5 ± 0.20	3.44 ± 0.10	2.05 ± 0.21

Similar mechanisms as suggested for SOC may be at play. In addition, the lack of the difference in total N between tree canopy and inter-canopy patches could be due to the fact that most of the soil samples collected under tree canopies were collected under *Terminalia sericea* (which is a dominant species in the park) and *Combretum* spp., which do not fix N. Many prior studies reporting tree impacts on soils have worked on N-fixing legumes such as acacia species (*Senegalia* and *Vachellia* spp.) (Belsky et al. 1989, 1993). Collectively, these data suggest that fire management at WPP will not have major impacts on soil N availability, at least in the relatively short-term management schemes investigated in this study.

Cations

We observed an increase in nutrients including available P, K, Na, Mg and Ca in the 1 year burned treatment. The increase in available P correlates to clay content (Tables 3 and 5). The correlation of available P to clay may indicate the extraction of exchangeable P from clay silicates. Sodium consistently decreased with increasing time since last burn. The sharp decrease in Na with increasing time since last burn may be due to vegetation utilisation by herbivores in the recently burned treatment relative to the treatments that burned long ago (14 and 24 years). Uunona (2014) reported that animals preferred recently burned treatments relative to those that have not been burned in a long time. This herbivore preference may have led animals to transfer Na from salt licks in the park into recently burned treatments through urine and droppings. In contrast, there was no clear trend for other exchangeable cations K, Mg and Ca; however, these cations were high in the recently burned treatment. This supports Cook (1994) who reported increased nutrient availability of P, K, Ca and Mg after fire in a nutrient-poor Australian savanna. In addition, Satyam and Jayakumar (2012) found that soil cations typically increase after fire because of their presence in the ash deposited from burning of aboveground biomass.

No significant interactive effect of fire and vegetation patch type were observed on soil nutrients or SOC. It may be that the fires that occurred in WPP were surface fires, which are prevalent in savanna systems, and that these fires were not sufficiently intense to significantly interact with tree canopies and have an interactive impact on soil resources. In contrast, increases in Mg and Ca under trees relative to inter-canopy spaces suggest that trees may be effective at concentrating nutrients from deep soils via roots uptake (Vanlauwe et al. 2005).

Conclusions

Fire history in Waterberg Plateau Park has a limited impact on soil nutrients and SOC content. This suggests that the fires in our study sites were not sufficiently intense to lead to significant losses through volatilisation or erosion. In addition, this may also suggest that in these nutrient-poor, sandy soils there is limited organic matter accumulation due to the low concentration of clay particles that efficiently bind to organic matter and base cations (Schimel et al. 1994; Schmidt et al. 2011). These results mirror those found previously in Kruger National Park, a similar ecosystem (Khavhagali 2008; Coetsee et al. 2010; Holdo et al. 2012). There was no significant impact of vegetation patch type on soil nutrients and SOC due limited spatial separation among tree canopies. It may be that the relatively high density of trees at our site and limited tree mortality from fire leads to more homogeneous distribution of roots in interspace than is typical of open savanas. Thus, differences among these fire treatments (and soil properties) may not be linked to time since last burn but rather to other factors that drive spatial variation. Our results suggest that management decisions regarding fire use in low-nutrient systems, such as our study area at Waterberg Plataeu Park, need not consider soil organic matter and nutrient resources among the primary concerns of fire frequency. Instead, management concerns regarding fire frequency should focus on other potential impacts of fire, such as plant community composition, forage production and quality, and animal habitat quality.

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