Preliminary assessment of the impact of long-term fire treatments on *in situ* soil hydrology in the Kruger National Park

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There has been significant attention focused on the impacts of fire frequency and season of burn on ecological processes in the Kruger National Park (KNP). Whilst there has been some examination of these fire effects on soil properties, the explicit linkages of these effects to the hydrology of soils in burnt areas has remained a gap in our understanding. During August 2010, a field scoping campaign was undertaken to assess the impacts, if any, of long-term fire treatments on the hydrology of soils on the experimental burn plots (EBPs) in the KNP. Using various hydrometric and soil physical characterisation instruments soil, hydraulic conductivity and soil strength variations were determined across the extreme fire treatment on the EBPs, the annual August (high fire frequency) plots and the control (no burn) plots, on both the granite and basalt geologies of Pretoriuskop and Satara, respectively. It was found that there were soil hydrological and structural differences to fire treatments on the basalt burn plots, but that these were not as clear on the granite burn plots. In particular, hot, frequent fires appeared to reduce the variation in soil hydraulic conductivity on the annual burn plots on the basalts and led to reduced cohesive soil strength at the surface.

Conservation implications: The KNP burn plots are one of the longest running and well studied fire experiments on African savannahs. However, the impacts of fire management on hydrological processes in these water-limited ecosystems remains a gap in our understanding and needs to be considered within the context of climate and land-use changes in the savannah biome.

Introduction

Savannahs are tropical grasslands with scattered trees; they occupy about 20% of the land surface of the Earth and 40% of Africa (Scholes & Hall 1996). These ecosystems are dynamic in their structure, composition and function. Fire is an important driver in savannah ecosystems, where it acts as both a generalist herbivore (Bond & Keeley 2005) and as a facilitator of the coexistence of trees and grasses (Higgins, Bond & Trollope 2000). The spatio-temporal availability of water is also considered a key driver of savannah heterogeneity (Walter 1971). Studies of catchment hydrological processes response to natural and induced fires have received the greatest attention in various land-systems within Australia (e.g. Brown 1972; Townsend & Douglas 2000). Studies elsewhere include mountain catchments under exotic forestry (Scott 1997) and fynbos (Lindley, Bosch & Van Wyk 1988) in South Africa; however, few studies have examined explicitly pyro-hydrological interactions and the role of various burning regimes within African savannahs (Scholes & Walker 1993).

Fire has long been used in the management of savannahs and this management has been informed and adapted by the findings of ongoing research on experimental sites of selected fire regimes on fixed areas (Andersen, Cook & Williams 2003; Knapp *et al.* 1998). The long-term fire experiment in the Kruger National Park (KNP) was established in 1954, with the initial objectives being to study the effects of fire frequency and season on the vegetation of the KNP under indigenous grazing pressure (Van der Schijff 1958). The experimental burn plots (EBPs) were laid out in four of the 37 main vegetation landscapes of the KNP described by Gertenbach (1983): the Pretoriuskop sourveld vegetation, Skukuza *Combretrum* vegetation, Satara Knobthorn and Marula vegetation and Mopani *Mopane* vegetation.

Whilst there has been some examination of fire effects on *in situ* soil properties, the explicit linkages of these to the hydrological parameters of soils in burnt areas has remained a knowledge gap (Pierson *et al.* 2011). To date, a variety of soil hydrological responses have been described; for instance, frequent burning reduced the rate of infiltration of rainwater into soil as noted in the Drakensberg (Bijker *et al.* 2001). This is caused by crusting of the soil, thereby yielding lower

electrical conductivity as a result of the removal of ash via increased surface water runoff and increasing soil erosion and as shown particularly for the granite EBPs in the KNP (Mills & Fey 2004). Webber (1979) showed that the unburnt control EBPs near Skukuza retained greater moisture levels well into the dry season and, where burning occurred on duplex soils, this made them susceptible to erosion.

In light of these previous findings, the objectives of this study therefore were to determine the impacts, if any, of long-term high fire frequency and intensity treatments versus fire exclusion on *in situ* soil hydrological characteristics in the KNP. Moreover, this included an assessment of the effects of potential fire impacts on soil hydrology in the two distinct geologies of the KNP: the granites and basalts.

Research method and design

The August 2010 field campaign focused on describing various *in situ* soil hydraulic and strength characteristics on these plots on the two extreme fire treatments, within an EBP string, on the two dominant geologies in the KNP, namely the granites at Pretoriuskop (Lowveld Sour Bushveld, sandy soils with mean annual precipitation [MAP] of 737 mm) and basalts at Satara (*Acacia nigrescens* savannah, clay soils with MAP of 537 mm) (Biggs *et al*. 2003). An EBP string is located generally along the crests of the hillslope and consists of twelve to fourteen 7 ha plots bounded by fire breaks to prevent natural and accidental fires from entering them. The fire treatments include winter August (dry season, hot), October (first spring rains), December (early summer wet season), February (late summer) and April (autumn) with annual, biennial and triennial treatments.

Because one string at both sites was deemed unrepresentative of the broader landscapes (Venter & Govender 2012), only three of the four strings at these sites were assessed, as shown in Figure 1.

A semi-systematic approach was taken in order to dismiss the inherent variability associated with the different soil morphologies linked to subtle changes in topography. Predetermined areas were selected according to diagnostic soil form characteristics, identified by a soil scientist (Le Roux pers. comm., 06 March 2010), which resulted in attention to sites characteristic of the Shortlands and Huttons soil forms (Soil Classification Working Group 1991) which were identified as being dominant on the basalt and granite plots, respectively. The reader is referred to Venter and Govender (2012) for detailed descriptions of the soil morphologies on the EBPs. Hydrological measurements and soil characterisations were then taken randomly within these areas.

A variety of techniques were used to determine the soils' hydraulic conductivity within 30 cm of the soil surface. These included:

- Double-ring infiltrometers, to determine saturated soil conductivities (K_{sat}) at the soil surface, according to the method of Lorentz *et al*. (2003).
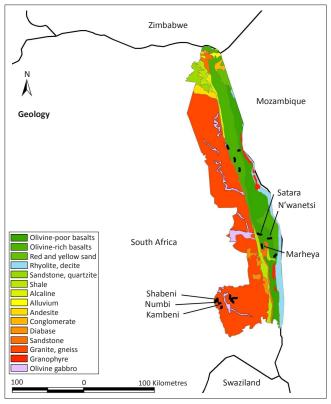

FIGURE 1: The Kruger National Park experimental burn plot strings assessed in this study.

- Guelph permeameters, to determine K_{sat} within the subsurface at 5 cm, 15 cm and 30 cm depths (Eijkelkamp Agrisearch Equipment 2008).
- Tension disc infiltrometers, to determine unsaturated soil conductivities (K_{unsat}) at the soil surface, according to the method of Lorentz *et al*. (2003).

Two replicates of each of the above techniques were made at each EBP treatment per landscape and results are discussed simply based on visual interrogation of the data. Sampling sites were selected in a semi-random manner by first identifying areas a minimum of 10 m from large trees and 15 m from the fire breaks and then randomly placing instruments on bare ground. The unconfined cohesive soil strength on the EBPs was assessed using the following equipment:

- a dynamic cone penetrometer (Herrick & Jones 2002), consisting of a 1 cm diameter rod, conical extremity of 90° and a 2 kg weight dropped from a height of 100 cm
- a pocket penetrometer (Eijkelkamp Agrisearch Equipment 2009)
- a pocket vane tester (Eijkelkamp Agrisearch Equipment 2011).

These assessments were performed within a 5 m radius of the hydrology measurements and typically 10 readings were taken at each of the EBPs randomly within the immediate vicinity of the soil hydrology measurements. The resulting data was then subject to non-parametric statistical analysis using the Mann-Whitney *U*-test for unmatched samples using the STATEXT v. 1.4 software (2011).
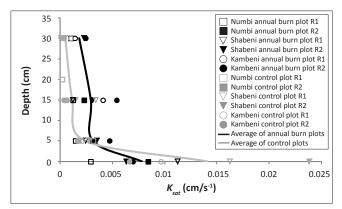
Results

The K_{sat} values determined at the soil surface of the granite EBPs clearly illustrate higher variation across all the plots and between fire treatments (Figure 2). Unfortunately, no measurements were taken on the Numbi control plot; however, it was noted that, for both replicates, the Shabeni control plots had significantly greater K_{sat} values than the annual burn plots. At Kambeni, the annual and control plots had similar K_{sat} values, although in both replicates the values were slightly lower for the control. The K_{sat} values for the basalt EBPs had generally lower variation than the granite EBPs (Figure 3). With the exception of Marheya Replicate 1 (0.015 cm/s^{-1} beyond the axis range), there appeared to be no distinct difference in the K_{sat} between annual or control treatments on the basalt EBPs.

The results of K_{sat} tests at depths between 5 cm and 30 cm (as depicted in Figure 2 and Figure 3) revealed that soils on the granite EBPs have, on average, a greater hydraulic conductivity on the annual frequent burn plots than the control plots; this was most noticeable at Kambeni and Shabeni. There was also a switch in the trend of K_{sat} where annual burn plots had lower K_{sat} at the soil surface than the control plots, a trend which reversed at depth. Interestingly, it appeared that there was less variation in K_{sat} at 5 cm within the control treatments on the granite EBPs. The K_{sat} distribution of the basalt EBPs, meanwhile, was an order of magnitude lower than the granite EBPs; however, there was no distinct difference in K_{sat} between annual and control treatments in the soil sub-surface.
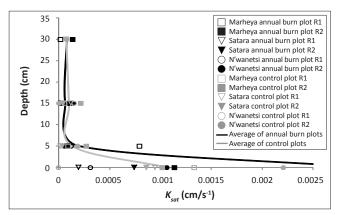
Figure 4 shows the K_{unsat} values of the granite EBPs soil surface, where, on average, the annual burn plots tended to have greater K_{unsat} than the controls. Also, there was a distinctly greater K_{unsat} on the annual burn plots at the lowest soil moisture tensions close to saturation (0.5 cm). The opposite trend of the annual EBPs having a lower K_{unsat} on average than the controls was demonstrated on the basalt EBPs (Figure 5). The outliers to the above trend on the basalt EBPs were the Marheya string and, with the exception of the Satara annual plot replicate, the controls had greater variation in K_{unsat} than the annual burn plots.

Drop cone penetrometer tests for granite EBPs revealed that the first approximate 150 J was the threshold for maximum depth penetration across annual and control plots; thereafter, there was a steady increase in depth at each energy increment (Figure 6). The greatest variations in soil strength properties were noted for control plots compared to annual burn plots on the soil of the granite EBPs. Whilst with the basalt EBPs (Figure 7), it was the annual plots which again had distinctly less variation in soil strength compared to the control plots. An interesting aspect depicted in Figure 7 was the slightly lower threshold in energy over depth, which was reached at about 130 J before further energy resulted in less depth penetration.

K_{sat}, saturated soil conductivities; R1, Replicate 1; R2, Replicate 2.

FIGURE 2: Field saturated hydraulic conductivity versus depth on the granite experimental burn plots in the Kruger National Park.

K_{sat}, saturated soil conductivities; R1, Replicate 1; R2, Replicate 2.

FIGURE 3: Field saturated hydraulic conductivity versus depth on the basalt experimental burn plots in the Kruger National Park.

Table 1 presents the statistical results of the raw drop cone penetrometer data at two energy levels (2 kg × 2 kg weight drops, or 34 J/cm^{-2} and 10 kg × 2 kg weight drops, or 307 J/cm^{-2}). There was no significant difference in the cohesive soil strength between control and annual burn plots on the granite EBPs; however, the basalt EBPs showed a significantly greater mean depth of penetration at both energy levels on the annual burn plots. The pocket penetrometer data supported this with no significant difference on the granite EBPs, but there was a statistical difference on the basalt EBPs. No significant difference was observed within the soil shear strength between annual and control treatments on both geological settings.

Trustworthiness

The data presented in these results are based on human measurements and thus aspects pertaining to the trustworthiness of the collected data need to be considered in the following contexts.
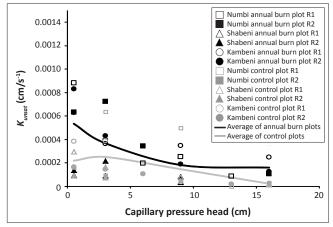
Reliability

Repeatability of acquiring the same results of both the K_{unsat} and K_{sat} measurements is achieved from standard *in situ* hydrological measurements. However, replication of

TABLE 1: Mann-Whitney U-test results for unconfined cohesive soil strength parameters in the Kruger National Park.

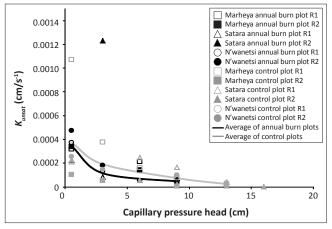| Instrument	Fire treatment	Basalt				Granite			
		N	Mean	U	p	N	Mean	U	p
Pocket penetrometer (Kg/cm^{-2})	Annual	62	2.51	1295.0	0.000	22	2.05	233.5	0.100
	Control	69	1.82			27	1.62		
Pocket vane tester (Kg/cm^{-2})	Annual	46	2.63	814.0	0.295	22	2.27	262.0	0.483
	Control	38	2.74			24	1.94		
Drop cone penetrometer (34 J/cm^{-2})	Annual	30	2.18	283.5	0.006	30	1.76	327.5	0.107
	Control	30	1.72			27	2.14		
Drop cone penetrometer (307 J/cm^{-2})	Annual	30	4.67	332.5	0.041	30	4.80	385.0	0.458
	Control	30	4.04			27	4.77		

No differentiation of the experimental burn plots string within the analysis.
N, number of observations; U, Mann-Whitney U statistic; p, probability of significance.

K_{unsat}, unsaturated soil conductivities; R1, Replicate 1; R2, Replicate 2.

FIGURE 4: Unsaturated hydraulic conductivity at the surface of the granite experimental burn plots in the Kruger National Park.

K_{unsat}, unsaturated soil conductivities; R1, Replicate 1; R2, Replicate.

FIGURE 5: Unsaturated hydraulic conductivity at the surface of the basalt experimental burn plots in the Kruger National Park.

the results would require the placing of the instruments at precisely the same locations, otherwise inherent heterogeneities in the soil matrix would yield different results. A potential observer bias arises when determining whether K_{unsat} and K_{sat} is reached at a steady-state infiltration rate. To ensure that this bias inherently did not affect the collected data, we followed the convention of 10 equal time intervals per volume of water infiltrated interval (for further details consult Lorentz *et al.* 2003).

The same principle applies for soil strength characteristics determined via the drop cone penetrometer method, where consistency of measurements is achieved by the dropping of a known weight from a standard height on the penetrometer device. However, reliability of the data may be questioned should the penetrometer not be held vertically above the soil. Care was taken during this study to ensure that each measurement was taken with a vertical deployment of the penetrometer device. Similarly, this principle also applies to the pocket penetrometer and pocket vane tester. However, we did observe a potential effect of pressure applied to the soil surface and angle of contact by these devices, meaning that each operator has the potential to influence the outcome of the measurement. To minimise this risk, the same operator conducted these measurements during this study.
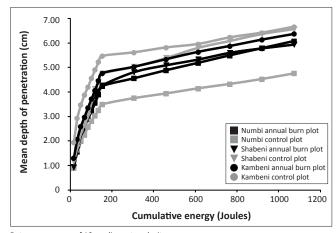
Validity

The validity of the reported measurements was believed by the authors to be appropriate to achieving the objectives of this scoping exercise within these specific study areas. Nevertheless, significantly greater replication of these measurements should be performed in future to quantify the variability of results from significant soil surface spatial heterogeneities on the EBPs and to answer comprehensively those causal mechanisms postulated in the following discussion.

Discussion

These measurements reveal interesting differences across the soils associated with the two geologies of granite and basalt in relation to long-term fire and no fire treatments. In the absence of greater spatial and temporal replication, the interpretation at this stage is speculative, but sets the scene for future data collection and analysis. Nevertheless, key aspects and questions from these initial interpretations and assessments should be explored further.
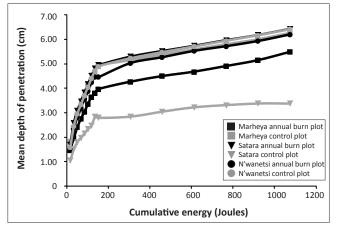
As expected, and as a result of their finer texture soils, the basalt EBPs have a K_{sat} distribution of an order of magnitude lower than the granite EBPs. Meanwhile, there is generally greater K_{unsat} at the surface on the granite EBPs annual burn plots versus the control plots, than compared to the similarity observed within the basalt annual burn and control plots.

Data are averages of 10 readings at each site.

FIGURE 6: Drop cone penetrometer data from the granite experimental burn plots in the Kruger National Park.

Data are averages of 10 readings at each site.

FIGURE 7: Drop cone penetrometer data from the basalt experimental burn plots in the Kruger National Park.

Furthermore, the K_{sat} at the surface is distinctly higher than at depth on the annual burn plots of the granite EBPs. These effects seen on the granite EBPs could be attributed to the loss of organic residues at the soil surface caused by long-term fire treatments, which would explain these higher K_{sat} and K_{unsat} values of the annual plots. As demonstrated by Fynn, Haynes and O'Connor (2003), organic carbon was significantly reduced within the first 2 cm of the soil profile under repeated grassland dry annual and biennial winter fire treatments at Ukalinga in KwaZulu-Natal. Similar results were described by Mills and Fey (2004) on the granite EBPs at Numbi, but also the Napi plots in the Skukuza EBP strings. Recently, soil carbon was also shown to be lower on dry annual burn plots than the controls in the Mopani EBPs on basalt (Holdo, Mack & Arnold 2011). Whilst the N'wanetsi string, also on basalt and following 30 years of fire treatment, showed a quarter lower organic carbon content in the control than on the annual, biennial and triennial burn plots (Jones *et al*. 1990).

The observed switch in K_{sat} trends between the surface and deeper layers, as noted on the granite EBPs, is also a point of interest. The differences noted at depths below the surface, such as K_{sat} and the soil strength, could simply be a result of inherent site differences such as soil morphological characteristics associated with different slope angles and position of measurements in the landscape; this is highly likely in the undulating landscape of Pretoriuskop. This points to the need for greater replication and spatial coverage in future studies of this type to isolate for such heterogeneous influences in the analysis. However, it is feasible that the lower K_{sat} on the annual plots on the granite EBPs soil surface may result from changes in the soils sorptivity resulting from ash deposition, the effects of which can be markedly variable depending on the texture of the soil (see e.g. Moody, Kinner & Úbeda 2009). This also points to the need in future to examine explicitly soil sorptivity characteristics resulting from fire.

However, the basalt EBPs show a smaller variation in K_{sat} and K_{unsat} on the annual treatments than the control plots, which may result from the development of a relatively homogenous soil layer structure on the more frequently burnt plots. This could be caused by a loss of organic matter and downward illuviation of finer material and ash deposits. The basis for this theory arises from two aspects. Firstly, the influence and importance of organic matter content on soil sheer strength is further demonstrated by Ekwue (1990), who showed that soil shear strength increased as a result of grass derived organic matter content. Therefore, the annually burnt basalt plots of the KNP have reduced soil strength as a result of a loss of organic carbon caused by frequent grassland vegetation fires at the site. This will make the soils on burnt areas within basalt both susceptible to erosion and have reduced soil moisture retention properties. The above results of deeper soil penetration per unit energy on the annual basalt plots described in this communication would support this hypothesis. Secondly, DeBano (2000) discusses the role of fires in facilitating the development of a water repellent layer in the soil subsurface. The frequent annual burning on the basalt EBPs could lead to the formation of a water repellent layer below the surface, rather than as a crust at the surface as suggested by Mills and Fey (2004). The small variation in K_{sat} at 5 cm on the basalt annual burn plots compared to the control plots is supportive of this theory, but warrants more detailed assessment, replication and analysis.

Seemingly, the same effects could also have occurred on the coarser soils of the granite EBPs. Whilst these may not be apparent within the limited analysis described here, the intricacies of different fire severities associated with soils of different textures on changes in aggregate stability warrants further determination (for a review see Mataix-Solera *et al*. 2011). Moreover, both granite and basalt EBPs showed high compaction beyond 5 cm soil depth in the penetrometer analysis and a concomitant similarity in K_{sat} between annual burn and control treatments beyond 5 cm. This suggests that fire effects on soil hydrology may be most significant within the first 5 cm of soil and should also be investigated further by analysis using parameters such as soil bulk density and rooting density, especially to complement further penetrometer data.

Results from this preliminary assessment of the impact of long-term fire treatments on *in situ* soil hydrology indicate that frequent hot fires lead to structural homogenisation of the soil surface particularly on basalt soils. Interpretation of this dataset requires cognisance of other recent findings on the effects of fire frequency and season on the KNP landscape. The reduction in woody vegetation cover as a result of frequent burning (Smit *et al.* 2010) and increase in small tree dominance under frequent burning (Higgins *et al.* 2007) are bound to have an effect on soil structure, as suggested by the scale dependent controls on biogeochemical processes resulting from tree canopy size (Holdo *et al.* 2011). Results will need to be discussed in this light. Whilst most interpretations and explanations have focused on the vegetation (both woody and grass) feedbacks on soil hydrological properties through a fire driven system, changes in herbivore utilisation and density (e.g. Burns *et al.* in review) and resultant trampling and nutrient deposition as a result of fire treatments also need to be considered.

Conclusion

This study indicated interesting geologically specific feedbacks between fire and soil hydrology. These need to be more thoroughly determined in order to quantify the impacts of soil crusting and water repellency resulting from fire on plant available water in the savannah landscape. The EBP experiment provides a valuable opportunity to explore the role of fire management policies on soil hydrological properties at point and plot scales, with the added benefit that the experiment allows for the inter-comparison between geological settings. The results presented here have suggested that the effects of fire management on soil hydrology become more apparent on the finer texture basalt soils than the coarser granites. However, future studies of this nature should be based on a more comprehensive, replicated and multifactorial analysis. These should focus on quantifying the variation of pyro-hydrological interaction both between geologies, but also the nuances that may be associated with fire frequency and intensity of burn within geologies, as well as an explicit assessment of the influence of slope and landscape position, amongst other aspects.

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Competing interests

The authors declare that they have no financial or personal relationship(s) which may have inappropriately influenced them in writing this paper.

Authors' contributions

E.S.R. (University of KwaZulu-Natal) was responsible for the methodological design, data collection and analyses used in this study. He was also responsible for analysing the results and compiling the manuscript. A.K. (University of KwaZulu-Natal), B.M. (University of KwaZulu-Natal), S.N. (University of KwaZulu-Natal), J.P. (University of KwaZulu-Natal), A.P. (University of KwaZulu-Natal), J.P. (University of KwaZulu-Natal) and Z.S. (University of KwaZulu-Natal) were responsible for data collection and analysis. S.A.L. (University of KwaZulu-Natal) contributed to the methodological design and was also responsible for data collection. N.G. (South African National Parks) provided the team with background information on the EBPs, logistical support during the campaign and made valuable contributing comments to the manuscript.

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