Calibration of soil charcoal as a proxy for paleofire in grassy systems: effects of environmental and burn variables in experimental burn plots

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Abstract

Grasslands account for 80% of annual burned area and as such are critical to understanding global trends in fire. To ask how fire regimes respond to climate changes and anthropogenic factors, we can study how fire activity has changed in the past using charcoal in soils and sediments. However, charcoal proxies have primarily been calibrated for middle-high latitude woody environments and not for grassy systems. We also imperfectly understand how these counts are affected by environmental and fire variables, such as rainfall, soil chemistry, burned area, and/or fire intensity. In this study, we evaluated charcoal proxies in a long-term savanna fire experiment in Kruger National Park, where regular burnings allow comparison of charcoal concentration against both environmental and fire regime variables to be quantified. We used charcoal counts to determine charcoal concentrations for the >150μm size fraction, which we statistically compared to burn conditions and environmental variables. We found that charcoal concentrations increased in long-term annually and biannually burned treatments vs. fire suppression treatments but was less sensitive to whether samples were collected before or after fire. Charcoal concentrations were generally higher in plots with clay-rich basaltic soil, possibly due to increased grass productivity or greater preservation potential of organic carbon. Understanding how these variables impact charcoal production during fire events allows for charcoal to be a more refined proxy when analyzing paleosols in grassy systems.

Introduction

Fire alters biogeochemical cycling and determines global biome distributions, making it an important Earth System process (Bowman et al., 2009). How fire will respond to anthropogenic factors and global climate change remains uncertain (Bond et al., 2004; Friedlingstein et al., 2022). By studying past fire history, we hope to be able to understand and predict modern and future changes in fire. Fire history reconstructions can be used to test how fire responded to changes in pCO2, temperature, and human activity in the past. Globally, savanna ecosystems burn most frequently, and account for >80% of annual global burned area (Van Der Werf et al., 2006, 2008), even though they account for only >25% of terrestrial area (Giglio et al., 2006). Therefore, to understand trends in global fire activity, we must focus on fire history of savanna ecosystems. Despite this, reconstructions of fire in grassy systems are under-represented in the literature (Duffin et al., 2008; Leys et al., 2017).

Paleofire history can be reconstructed using environmental proxies, which is one method that allows us to investigate attributes of past fire events, including burn area, fire intensity, and other fire conditions. A variety of proxies can infer these attributes; one such proxy is charcoal concentration in soil (Conedera et al., 2009). Although grasslands contribute to global fire dynamics, the majority of charcoal-based research and calibrations are from mid-high latitude forested systems (Duffin et al., 2008; Aleman et al., 2013; Leys et al., 2015). Grassy fire regimes are often quite different from those in forest systems. Fire occurs more frequently in grasslands, and environmental variables, such as rainfall, can have opposite effects on fire activity between grassy and forest systems (Bradstock, 2010; Leys et al., 2017). Additionally, charcoal peaks in forest systems are sometimes interpreted as individual fire events rather than long-term averages of fire history (Ali et al., 2009; Higuera et al., 2011). However, this does not seem to apply in grassy systems, where fire is much more frequent (Duffin et al., 2008; Leys et al., 2017). For these reasons, we cannot rely on charcoal proxy calibrations conducted in forest systems to interpret charcoal records from grassy systems.

Soils are useful archives that preserve local records of vegetation and fire history. Measuring a proxy in soils with known environmental and fire conditions allows us to study how variability of conditions in space rather than time may affect how charcoal concentrations, as well as understand how charcoal may preserve information about fire history on a local scale (Ohlson and Tryterud, 2000; Egli et al., 2012). This is a complementary approach to examining charcoal in core top sediments, which integrate conditions over a wide area though time, and are additionally influenced by transport processes (Leys et al., 2017). To the best of our knowledge, no study has examined if and how environmental and burn conditions effect soil charcoal concentrations in savannas that have been experimentally burned. Here, controlled burn sites at Kruger National Park act as a framework to examine charcoal as a proxy. We examine the charcoal content of 33 samples from 3 different landscapes with varying environmental conditions. These sites have been burned at a consistent fire frequency by managers for the last 70 years. This experimental framework allows us to test several fundamental questions about what factors control soil charcoal concentrations in soils. First, we examine the temporal scale of how fire events and regimes are recorded in soil charcoal concentrations. We test two alternative hypotheses: H_A) that soil charcoal concentrations record the most recent fire at a site or H_B) that soil charcoal concentrations record the long-term fire history of a site. We also investigate whether and how environmental conditions, such as rainfall, biomass, and soil properties, influence soil charcoal concentrations. To answer these questions, we measured charcoal concentrations for sites that have never been burned, as well as concentrations pre-burn and post-burn at sites that are regularly burned (annually and biannually). We compare charcoal concentrations to environmental site conditions, as well as burn conditions, to determine which, if any, have an impact on the amount of charcoal found in soil.

Methods

We collected soil samples from Experimental Burn Plots (EBPs) in Kruger National Park, South Africa. This long-standing experiment was initiated in 1954 as a means of researching the long-term impacts of fire across multiple landscapes (Biggs et al., 2003). The EBPs consist of strings of plots with different treatment types, which are replicated multiple times across each landscape. The soil samples we collected are representative of annual and biannual August burns, as well as unburned control plots.

The 11 samples from the upper 1 cm of soils were sampled randomly at 10-meter intervals. We then homogenized, sub-sampled, and oven-dried the samples at 40°C for 12 hours. A 2cc dry sample was taken with a syringe, and the weights of the samples were measured in grams. Samples were treated to chemically remove organic matter and deflocculate particles. We added 4 ml of 20% sodium hexametaphosphate solution to the centrifuge tubes and 10ml of concentrated bleach. The samples were shaken by hand, left to sit for 24 hours, shaken again and left to sit for another 24 hours. We centrifuged the samples at 3000 rpm for 3 minutes, then decanted them. The centrifuge tubes were filled with DI water to the 25ml mark, and were again centrifuged and decanted. We rinsed the samples into a sieve stack of 125μm and 60μm, saving the <60μm fraction with DI water. The samples were rinsed with DI water until no longer muddy. The fully washed size fractions (125μm, 125-60μm, <60μm) were then rinsed off the sieves into respective centrifuge tubes. Charcoal from the largest size fraction was poured into petri dishes to be counted. Petri dishes were placed on grid paper with a grid size of 1mm^2, and were examined under the microscope at a magnification of 2.5x. All charcoal on the dish was counted. Charcoal counts were normalized both by volume and weight.

We used statistical analysis in order to determine the extent to which the number of particles of charcoal varies with environmental and fire regime characteristics, as well as observed burn conditions. Models were determined for both the amount of charcoal/g and charcoal/cc. We calculated linear regressions using ANOVA analysis to determine charcoal concentration variation due to sample type, location, and replicate. Pairwise T-tests were performed as an analysis of charcoal variation in regards to the variables listed above, via comparison of sample means. We then subsetted the data to exclude the B2 burn frequency samples, and these analyses were repeated in order to assess if differences in fire frequency and plot site may be overshadowing the variables of interest. To determine an accurate model for the effects of the burn conditions, we subsetted the post-burn samples for analysis, as these variables should only impact the burned plots. A multiple linear regression based on environmental and fire variables was determined using Akaike information criterion (AICc) model selection, a method for evaluating possible models that addresses both over-fitting and under-fitting of the data. We chose the best model to be the simplest model with ΔAICc<2. We used Tukey's Honest Significant Difference Test to evaluate differences of means between treatment groups. Analyses were performed in R v.2023.06.2, using the “lme4”, “lme4”, “AICcmodavg”, “MuMIn”, “visreg”, “lmerTest”, and “TukeyHSD” packages.

Results

First, we examined how charcoal concentrations varied across EBP plots, treatments, and sample types. We conducted ANOVA analysis considering samples across all observed fire treatments. Due to the experimental design, we examined models using both nested and non-nested structures for predictor variables (landscape, replicate, treatment, sample type). We used square root transformation on the charcoal concentration. The best model included treatment (no fire, annual fire, biannual fire) and landscape (Pretoriuskop, Skukuza, Satara) as independent predictor variables (Table 1). Treatment was the most statistically significant predictor of charcoal concentration (N=43, F=32.602, p=5.7e-09), followed by landscape (N=43, F= 8.028, p= 0.00124). Because we did not collect paired pre-burn samples from the (biannual) treatment, we worried that lumping all post-burn samples together was biasing the influence of treatment on the post-burn sample group.

We therefore repeated ANOVA excluding biannual post-burn samples and not considering treatment. The best model, selected based on AICc values, included sample type (no fire, pre-burn, post-burn) and landscape as independent predictor variables. Sample type was a statistically significant predictor of charcoal concentrations (N=33, F=31.536, p=6.74e-08), as well as landscape (N=33, F= 8.571, p=0.00125).

We used Tukey’s Honest Significant Difference Test to evaluate which groups had the largest and most significant differences in the means. Control plots had significantly less charcoal than both pre-burn (μ= -40 counts/g, p=0.0008) and post-burn soils (μ= -64 counts/g, p=1E-7) (Fig. 1). Pre-burn and post-burn soils did not have significantly different charcoal concentrations (p=0.27; Table 3; Fig. 1). Pretoriuskop soils had significantly more charcoal (μ=18 counts/g, p=6E-6) than Skukuza soils (Table 3).

However, Satara soils did not have significantly different charcoal concentrations than either of the other landscapes (Table 3). The same relationship as described in Figure 1 can be seen across locations (Fig. 2).

These analyses were performed using charcoal concentration, measured as both charcoal counts per gram and charcoal counts per cubic centimeter. The results of modelling and analysis were comparable, and so all data is shown in charcoal/g.

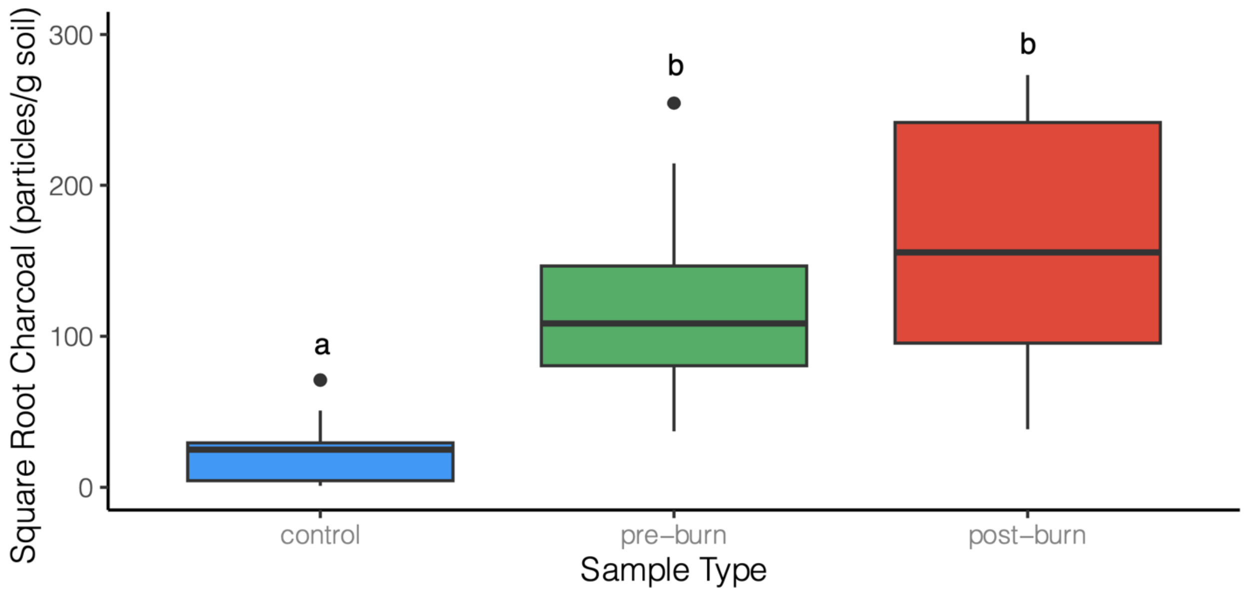

Figure 1: Charcoal concentration according to the three sample types: control, pre-burn, and postburn. Charcoal concentrations were measured in charcoal particles per grams soil, and did not include biannual post-burn samples. Letters indicate groups were significantly different at a p<0.0001 level (***), which was determined via ANOVA.

Table 1: AICc minimization for the square root of charcoal concentration for ANOVA between experimental conditions for all treatments. Charcoal concentrations are measured in particles/gram for samples of >150μm size fraction. Variables tested for in AICc model selection include landscape (Pretoriuskop, Skukuza, Satara), experimental replicates, treatment (no fire, annual fire, biannual fire), sample type (no fire, pre-burn, post-burn). Nested and non-nested structures were considered. Selected model is in bold text.

$\sqrt{(Charcoal\ Concentration)}$	Degrees of Freedom	ΔAIC
Landscape+Treatment	6	0.00
Landscape+Treatment+Sample Type	7	1.54
Lanscape+Sample Type	6	8.39
Full Model: Landscape/Replicate/Treatment +Landscape/Replicate +Sample Type+Landscape+ Replicate+Treatment	34	259.32
Null	2	39.15

Table 2: AICc minimization for the square root of charcoal concentration for ANOVA between experimental conditions with biannual post-burn samples excluded. Charcoal concentrations are measured in particles/gram for samples of >150μm size fraction. Variables tested for in AICc model selection include landscape (Pretoriuskop, Skukuza, Satara), experimental replicates, sample type (no fire, pre-burn, post-burn). Nested and non-nested structures were considered. Selected model is in bold text.

$\sqrt{(Charcoal\ Concentration)}$	Degrees of Freedom	ΔAIC
Landscape+Sample Type	6	0.00
Sample Type	4	9.96
Replicate+Sample Type	14	17.83
Full Model: Landscape/Replicate +Sample Type+Landscape+ Replicate	14	17.83
Null	2	33.78

Table 3: Tukey's multiple comparisons of the means for the square root of charcoal concentrations for ANOVA between experimental conditions with biannual post-burn samples excluded. Charcoal concentrations are measured in particles/gram for samples of >150μm size fraction. Italics indicate groups were significantly different at a p<0.001 level (**). Italics and bold indicate groups were significantly different at a p<0.0001 level (***).

Groups compared	Difference in $\sqrt{(Charcoal\ Concentration)}$	Difference in charcoal (concentration/g soil)	p-value
		Location	
Satara-Pretoriuskop	-1.789607	-3.202693	0.2521303
Skukuza-Pretoriuskop	*-4.209007*	*-17.71574*	*0.0008456***
Skukuza-Satara	-2.419401	-5.853501	0.0892647
		Sample Type	
post-burn-control	***8.023362***	***64.37434***	***0.0000001****
pre-burn-control	***6.331209***	***40.08421***	***0.0000062****
pre-burn-post-burn	-1.692154	-2.863385	0.2670293

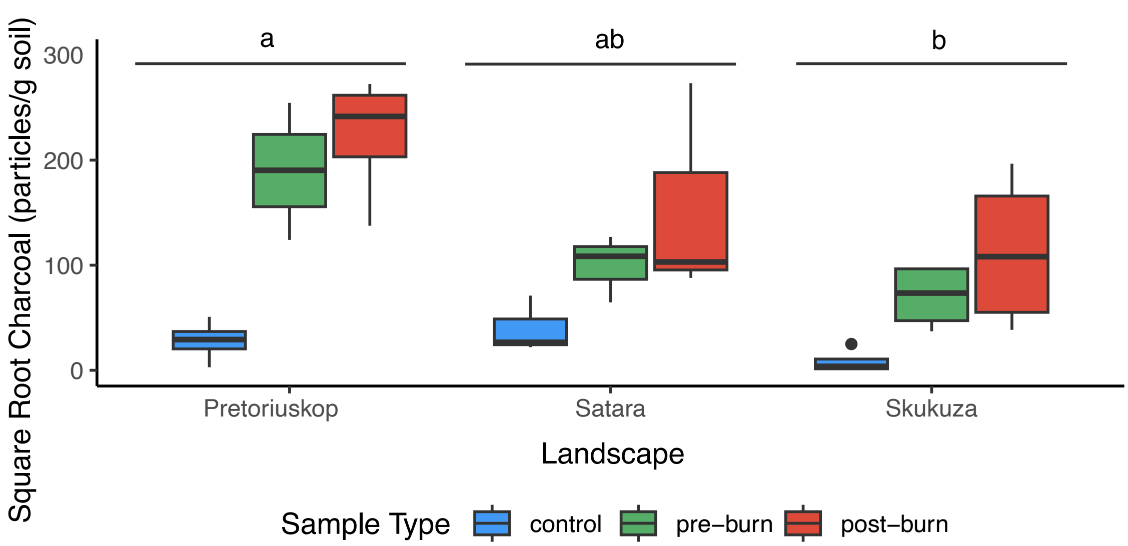

Figure 2: Bar chart of charcoal concentrations by landscape and sample type, with biannual post-burn samples excluded. Letters indicate groups were significantly different at a p<0.001 level (**), which were determined via Tukey's multiple comparisons of the means.

Since charcoal concentrations were significantly variable across landscapes, we examined if particular environmental conditions were significant predicators of charcoal concentrations. Because August B1 (annual burn) plots were the only treatment where we measured both pre- and post- burn samples, we excluded pre-burn samples from this analysis. We used AICc to select for the best model among models including rainfall (mm), soil bedrock type, fire frequency (which was modeled as a quadratic relationship), and above ground biomass (mg/ha). The best model included soil type and fire frequency as significant variables (Table 4). Charcoal concentrations were maximized at intermediate fire frequencies (Figure 3). Charcoal concentrations were also generally higher in plots with basaltic soil, compared to granitic (Figure 3). Results were comparable for both charcoal/g and charcoal/cc.

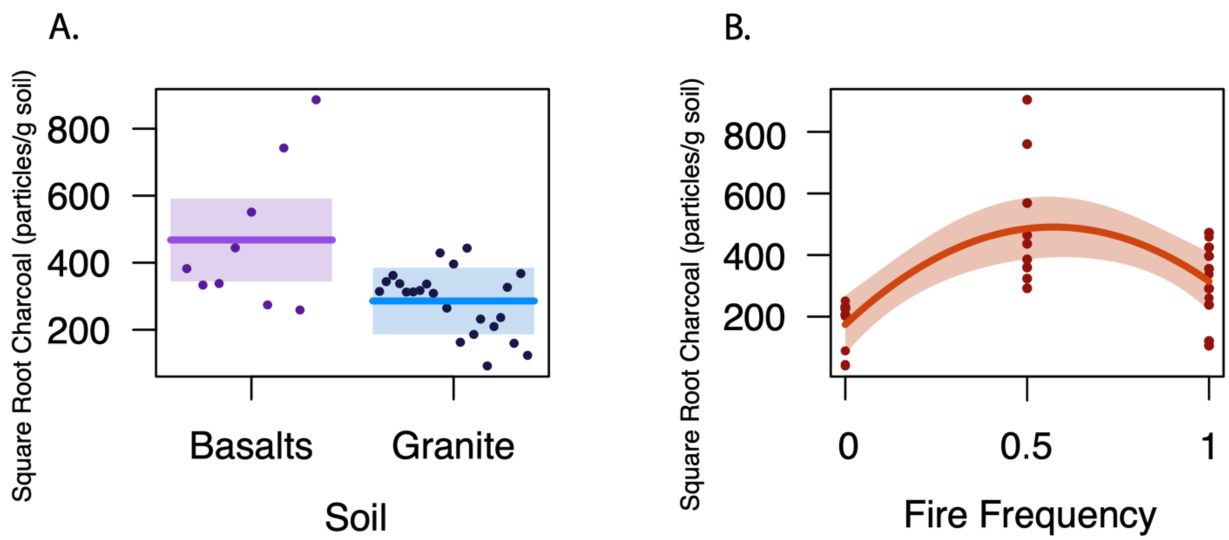

Figure 3: Best model from AICc model selection, including soil bedrock type and fire frequency. Fire frequency occurs every two years (0.5), every year (1), or never (0) for control sites.

Table 4: AICc minimization for the square root of charcoal concentrations for environmental variables. Charcoal concentrations are measured in particles/gram for samples of >150μm size fraction. Variables tested for in AICc model selection include rainfall (mm), soil bedrock type (basaltic or granitic), fire frequency, and above ground biomass (mg/ha). Selected model is in bold text.

$\sqrt{(Charcoal\ Concentration)}$	Degrees of Freedom	ΔAIC
Fire frequency + Fire frequency2 + Rainfall + Soil	6	0.00
Biomass + Fire frequency + Fire frequency2 + Soil	6	1.64
Fire frequency + Fire frequency2 + Soil	5	1.65
Full Model: Biomass + Fire frequency + Fire frequency2 + Rainfall + Soil	7	3.28
Null	2	31.59

We also tested if the conditions of the fires themselves were related to the concentration of charcoal in post-burn samples. We used AICc to select for the best model among models including fire frequency, fuel moisture content (FMC;%), fuel load (mg/ha), air temperature (C), humidity (RH;%), wind speed (m/s), rate of spread (ROS;m/s), fire intensity (kW/m), and estimated % burned. The selected model was the null model (Table 5). The selection of the null model indicates that none of the eight considered burn conditions are strong predictors for charcoal deposition.

Table 5: Akaike Information Criterion (AIC) minimization for the square root of charcoal concentrations for burn condition variables. Charcoal concentrations are measured in particles/gram for samples of >150 μm size fraction. Variables tested for in AICc model selection include fire frequency, fuel moisture content-FMC (%), fuel load (Mg/ha), air temperature (C), RH (%), wind speed (m/s), ROS (m/s), fire intensity (kW/m), and estimated % burned. Selected model is in bold text.

$\sqrt{Charcoal\ Concentrations}$	df	ΔAIC
Fire frequency	3	0.00
Fire frequency + Fire intensity	4	1.18
Estimated burned area + Fire frequency	4	2.52
Full Model: Fuel load + Air temp, RH + wind speed + ROS + fire intensity + estimated % burned		
Null	2	0.13

Discussion

This study aimed to evaluate macrocharcoal as a paleoenvironmental proxy for fire, by investigating whether most-recent fire conditions (H_A) or long-term fire conditions (H_B) had greater effects on charcoal concentrations, and if charcoal concentrations are related to environmental conditions. In order to accomplish this, we compared charcoal concentrations in soils taken from the long-term experimental burn plots (EBPs) at Kruger National Park, South Africa. Samples were collected from sites before and after prescribed burns, as well as sites that had not been burned for the duration of the experiment (70 years).

Charcoal sampling

To test if long-term fire or single fire events had a greater effect on soil charcoal we compared charcoal concentrations in pre-burn, post-burn, and control samples from the experimental burn plots. Results of ANOVA analysis showed that pre-burn and post-burn samples were statistically indistinguishable, while control samples had significantly less charcoal than both pre-burn and post-burn samples (Fig. 1; Table 3; Fig. 2). This indicates that the single burn event does not significantly alter the charcoal concentrations in the upper centimeter of soil, and allows us to reject the hypothesis that most-recent fire conditions have an outsized effect on charcoal concentrations (H_A). Rather, this analysis indicates that soil charcoal concentrations better represent long-term fire conditions and the past six decades of fire history (H_B), supporting previous findings (Duffin et al., 2008; Conedera et al., 2009; Aleman et al., 2013).

Moreover, none of the most-recent fire conditions were significantly related to charcoal concentrations (Table 5). Burn conditions were measured on site during the fire event, and are therefore representative of the single most-recent burn event. This is consistent with our finding that charcoal collected immediately following a fire event was not significantly greater than before the event. This result again favors the hypothesis that soil charcoal more accurately represents long-term fire conditions. Notably, Duffin et al. (2008) measured charcoal in reservoir sediments in Kruger National Park and found that the charcoal record was most strongly correlated to the previous 5 years of fire history in grassland systems, rather than singular fire events (Duffin et al., 2008). Other studies on grassy systems have found charcoal concentrations to be correlated with a variety of long-term fire variables, including fire proximity, burned area, and fire intensity (Duffin et al., 2008; Leys et al., 2017). These studies were performed on lake-sediments, and so these burn condition variables are representative of burn characteristics over a longer time scale, as opposed to the single event measurements taken in our study. Moreover, the areas that were studied generally had lower fire frequencies than those at KNP sites, possibly resulting in further differences in resolution (Duffin et al., 2008; Leys et al., 2017).

Fire frequency was also significantly related to charcoal concentrations in the EBP soils (Fig. 3; Table 4). Correlation between fire frequency, a variable that reflects long-term fire history, but not the conditions of the most recent fires themselves, further supports the conclusion that charcoal concentrations best represent long term fire history. Other charcoal calibration studies on grassy systems have found differing results; Leys et al. (2017) found that area burned, rather than fire frequency, explains charcoal concentrations (Leys et al., 2017). However, this is likely because charcoal was measured in sediments through time rather than soils spatially at sites with different fire frequencies.

Environmental conditions

Soil bedrock type and fire frequency partially explained soil charcoal concentration. However, other variables, including biomass and rainfall, were not selected for as predictors.

Sites at KNP represent landscapes with either basaltic or granitic underlying bedrock. Multiple regression analysis indicated greater charcoal concentrations were found at sites with basaltic rather than granitic bedrock (Fig. 3; Table 4). Basaltic bedrocks tend to produce soils with more clay, while granitic bedrocks tend to result in sandier soils, due to differences in mineral content and weathering processes (Staver et al., 2017). Increased clay content in basaltic soils could impact charcoal concentrations through two possible mechanisms.

Firstly, clay content and minerals have been seen to be associated with organic carbon preservation (Ladd et al., 1985; Schimel et al., 1985; Wiseman and Püttmann, 2005), although more recent studies suggest that organic carbon is better preserved via oxide binding (Wiseman and Püttmann, 2005). Here, it is suggested oxides in soils mediate organic carbon preservation, as clay minerals have affinities for binding to positively charged oxides (Goldberg, 1987), which in turn bind to negatively charged organic carbon particles (Kaiser et al., 2001; Wiseman and Püttmann, 2005). Thus, organic carbon bonds more strongly to the soil matrix, which increases the preservation potential on clay-rich soils. If this is the driving mechanism behind the observed trends in our data, then the correlation between greater charcoal concentrations and basalt-derived soils may be partially due to preservation biases.

However, bedrock mineralogy can also impact vegetation community and biomass. Soils with higher clay content often result in increased grass biomass, due to higher nutrient retention, as well as differences in hydrologic characteristics that favor grass growth over tree growth (Staver et al., 2017).

Grass biomass drives fuel loads during burn events (Shea et al., 1996; Archibald et al., 2018). Greater fuel loads produced through this process could explain the increased charcoal concentrations at sites with basaltic clay soils. Higher grass biomass would mean more fuel to burn during fires and greater charcoal production. If this is the driving mechanism behind the observed trends in our data, the correlation between greater charcoal concentrations and basalt-derived soils would reflect greater fuel loads driving increased charcoal production.

It is important to note that aboveground biomass was not selected for as a statistically significant variable in the environmental conditions model (Fig. 3; Table 4). At first this suggests that site biomass is not a driver in charcoal production, and therefore increased productivity due to basaltic soil bedrock would not explain the observed trends (Fig. 3). However, the nature of this data means we still cannot dismiss this hypothesis. The biomass data included in our model includes both tree and grass biomass (Singh et al., 2023), and because trees have relatively more aboveground biomass than grasses, they dominate the patterns in the aboveground biomass. However, grass material is largely what is burned during fire events, contributing 70-98% of total fuel in African savanna fires (Shea et al., 1996; Archibald et al., 2018), and thus grass biomass drives fire. To explicitly test the hypothesis that increased productivity is what led to higher charcoal concentrations in basaltic soils, we would need data about grass biomass, rather than combined tree and grass biomass.

Grass biomass was measured as one of the burn condition variables, ‘Fuel load’, and was included in the fire condition models. Fuel load was not selected for when modelling burn condition variables (Fig. 3). However, as discussed in the section prior, our study demonstrates that charcoal concentration is more closely linked to long-term fire conditions, rather than most-recent fire conditions. Fuel load reflects a one-time measurement taken before burning, and only reflects conditions before the most-recent fire.

Biomass itself is strongly influenced by fire frequency; up to an extent, longer fire intervals allow for more vegetation growth, increasing biomass (Govender et al., 2006). This correlation is not linear;

rather the relationship between fire frequency and biomass is best described as quadratic (Collins, 1992). At a certain point, longer fire intervals become detrimental to productivity in grassy systems. We also observe a quadratic relationship between fire frequency and charcoal concentrations in the EBP soils. Sites that were burned every other year were found to have significantly higher charcoal concentrations when compared to sites that were burned each year. This supports the interpretation that sites that are burned every other year experience greater grassy plant growth between burns, thus increasing available biomass and average fuel load. This is consistent with the hypothesis that more material burned produces more charcoal.

Rainfall is also considered to be responsible for increases in grassy biomass, with fuel loads increasing with rainfall for the first 4-5 years after a fire event (Govender et al., 2006; Sala et al., 2012). However, our study did not find rainfall to have significant effects on charcoal production, supporting previous findings (Leys et al., 2017). There are multiple reasons why this may be the case. The first is that the relationship between rainfall and burn area is quadratic (Archibald et al., 2012; Alvarado et al., 2020); studies have suggested that an intermediate amount of rainfall results in greater fire spread in grasslands (Meyn et al., 2007; Bradstock, 2010; Krawchuk and Moritz, 2011; Archibald et al., 2018). In grasslands, this hypothesis is based on the notion that if rainfall is too low, fuel loads are low and are the limiting factor for fire, while if rainfall is too the fuel is too wet and fuel moisture is the limiting factor (Bradstock, 2010; Cardoso et al., 2022). An intermediate amount of rainfall results in high grassy biomass and lower fuel moisture, supporting fire spread. This interplay between fuel load and fuel moisture could partially explain why rainfall increases do not strictly correlate to increases in soil charcoal. Additionally, it is possible that soil charcoal does not correspond to rainfall increases due to correlations between rainfall and tree biomass. Previous findings show that rainfall has important impacts on tree biomass, specifically that systems with greater rainfall can support more trees (Lawes et al., 2011; Murphy et al., 2015). As there is no metric to differentiate between tree and grassy biomass in this study, the relationship between rainfall and tree biomass cannot be quantified.

Implications

We found that soil charcoal records long-term fire histories in savannas at a landscape scale, and is not affected by individual fire events. This indicates that the most recent fire does not over-write the last few decades worth charcoal production and deposition. Ideally, a proxy should represent the past broadly, rather than by few individual events. Our results indicate that the former is the case for charcoal, giving us more confidence that in grassland soils charcoal is faithfully recording long-term fire history.

We also found that environmental conditions affect charcoal concentrations in soil, either through preservation or production processes. This is important to keep in mind when interpreting charcoal as a proxy for fire history. If biomass production is indeed the mechanism driving increased soil charcoal, substantiated by some past studies (Aleman et al., 2013), charcoal records can be interpreted as changes in fuels burned in historic fires. Using charcoal as a proxy for fuel load in past savanna systems could allow further research into changing fire regimes and could be used for very interesting comparisons between fire in the past and fire today.

However, it is also important to acknowledge that preservation biases may skew data. This would result in basaltic landscapes having higher charcoal concentrations when compared to granitic sites with the same fire history, leading to incorrect assumptions about past fires. If indeed soil bedrock lithology impacts charcoal preservation, this bias would need to be taken into account when using charcoal as a proxy.

Future Directions

These samples can be used to further calibrate other aspects of charcoal measurements beyond what we measured in this study. Here, we only looked at the largest size fraction, >150um, but more information may be found in the smaller size fractions. Macrocharcoal tends to account for local charcoal deposition, maximally travelling 5km from the burn site in grassy systems (Duffin et al., 2008; Aleman et al., 2013; Leys et al., 2015), although some studies have predicted this distance is smaller (Leys et al., 2017). On the other hand, smaller size fractions can be carried further and are thought to represent a more regional fire history. Smaller size fractions may show different trends than those seen in the >150um faction, so further research could reveal different exciting ways that charcoal can be used to understand fire in the past.

Additionally, looking at smaller size fractions could give insight into different aspects of past burns, including fuel type. The size of charcoal particles may disproportionately represent different fuel types. Grassy fuel types produce smaller charcoal particles, and therefore it is recommended to count charcoal particles over 60μm (Leys et al., 2017). Different trends pertaining more to the grassy biomass may be seen in smaller size fractions than measured in our study.

Insight about the type of biomass burned can also be determined from charcoal shape. It has been found that the length to width ratio of particles correlates to fuel type and can be used to distinguish between grassy and woody fuel sources (Aleman et al., 2013; Leys et al., 2015, 2017; Vachula et al., 2021). Measures of size and shape could possibly demonstrate different trends when compared to the same landscape variables and burn conditions.

Additionally, collecting long-term grass biomass may help to confirm if relationships between fire charcoal, frequency and soil bedrock mineralogy reflect are due to charcoal production rather than preservation.

Conclusion

Our study aimed to calibrate soil charcoal as a proxy for paleofire in savannas, and determine what, if any, fire history information is preserved in soil charcoal. We examined the effects of environmental and burn conditions on charcoal concentrations using experimental burn plots in Kruger National Park as a framework. When we compared charcoal concentrations in pre-burn, post-burn, and control samples, we found data in support of H_a, that charcoal as a proxy is representative of long-fire conditions in grassland systems, rather than most-recent fire conditions. Moreover, analysis of burn conditions also demonstrated support of H_a, as we found no correlation between most-recent fire condition variables and charcoal concentration.

Both fire frequency and soil bedrock type had an apparent effect on soil charcoal. Basaltic soils generally had higher charcoal concentrations, possibly due to either preservation biases or being indirect measures of grassy biomass. Lower fire frequencies were also positively correlated with charcoal concentrations, likely as the result of also being an indirect measurement of grassy biomass. Other environmental variables, including rainfall and biomass, were unable to explain variation of charcoal concentration measurements. These correlations indicate that charcoal may be able to preserve information about long-term past fire conditions, and also that it may be useful to consider preservation biases when using soil charcoal as a proxy.

An ideal proxy represents a broad view of the past, and is not over-written or over-represented by few individual events. The results of our analysis indicate that charcoal concentration accurately represents long-scale fire histories, rather than short-scale fire events. Furthermore, information about long-term past fire may be faithfully preserved in soil charcoal, allowing additional information to be incorporated into fire history reconstructions based on soil charcoal.

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