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Frequent prescribed fire contributes to soil organic carbon sequestration and pyrogenic carbon stability in South African mesic grasslands

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Abstract

Grasslands serve as crucial terrestrial carbon sinks, storing substantial amounts of organic carbon (OC) in aboveground vegetation, roots, and soils. However, effective carbon sequestration in grasslands depends on management practices. South African subtropical mesic grasslands are fire-adapted ecosystems, dependent on fire as a key ecological force shaping and sustaining them. Fire influences carbon sequestration by removing above-ground biomass, redistributing nutrients, and contributing inputs through thermal mineralisation.

This study assessed the impact of varying fire frequencies and season of prescribed burns on soil organic carbon (SOC) stocks, total nitrogen (TotN), and carbon-to-nitrogen (C:N) ratios, as well as the stability of refractory organic matter (refractory OM) and black carbon (BC) fractions across soil depths up to 30 cm. Results showed that fire frequency and season of prescribed burns significantly influence SOC and TotN stocks, with annual winter and spring burns resulting in the highest SOC stocks and wider C:N ratios in the top 5 cm of soil. Conversely, biennial and triennial burns showed reduced SOC stocks, with triennial burns displaying the lowest levels and even SOC loss below 5 cm. Over 20 years, SOC stocks increased under all fire regimes except for triennial burns, where stabilization or reduction was noted.

Additionally, our findings indicate that increased fire frequency leads to the maintenance of BC within the soil, though BC remains stable across soil horizons. Refractory OM and BC levels were greater in areas that were unburnt or experienced longer burn intervals, likely driven by a decline in soil pH and increased acid saturation associated with less frequent fires. These patterns suggest that while regular fires can contribute to surface SOC stocks, the management of fire intervals is crucial for maintaining deeper, more recalcitrant carbon fractions. This emphasizes the beneficial role of regular grassland fires in carbon sequestration and suggests practical management strategies for fire-adapted mesic grasslands.

Introduction

Grasslands serve as crucial terrestrial carbon sinks, storing significant amounts of carbon in aboveground vegetation, roots, and soils (Bikila et al., 2016; Ward et al., 2016). The management practices applied to these ecosystems play a central role in determining their carbon storage potential (Ward et al., 2016). Prescribed fire management is a common practice in South African grasslands, but its long-term sustainability remains a concern due to carbon and nitrogen losses from biomass during burns (Materchera et al., 1998; Snyman, 2002). Understanding the timing and frequency of prescribed fires is essential for ensuring the long-term sustainability of grasslands and maximising their carbon sequestration potential.

While grasslands managed with prescribed fire have demonstrated substantial carbon sequestration (Teixeira et al., 2022), the specific impact of fire frequency and season of prescribed burns on soil organic carbon (SOC) stocks, total nitrogen (TotN), and carbon stability remain poorly understood. In this context, carbon stability refers to the presence of stable, recalcitrant carbon (RC), a fraction of soil organic matter (SOM) that is resistant to decomposition and is a key to long-term carbon storage. This study examines the maintenance of stable carbon fractions as concentrations through soil depth and evaluates total carbon sequestration over time by comparing current SOC stocks to those measured in 2001 by Fynn et al. (2003), allowing for an assessment of carbon accumulation over a 20-year period. The Ukulinga Grassland Fire Experiment (UGFE), established in 1950 in the subtropics where rainfall is summer-dominant, provides a unique opportunity to examine carbon stocks and turnover following prescribed fire treatments (Fynn et al., 2003). Studies from the UGFE suggest that seasonal burns, particularly in spring, mitigate carbon losses by facilitating rapid litter decomposition and incorporation into soils before burning, while autumn and winter burns reduce surface carbon pools through wind erosion and leaf litter removal (Fynn et al., 2003).

Fire has been noted to influence the turnover of stable carbon fractions such as black carbon (BC) and refractory organic matter (refractory OM), critical for long-term carbon storage (Gao et al., 2017; Glaser & Amelung, 2003). These RC forms resist decomposition, yet their distribution and stability across soil depths may be shaped by fire frequency and soil acidification (Findlay et al., 2022; Masiello, 2020). Suppressed fire regimes can maintain soil acidity in already acidic soils, limiting microbial activity and SOC turnover or availability. In contrast, low-intensity fires, through the deposition of alkaline mineral ash containing inorganic carbonates (e.g., calcium, magnesium, sodium, potassium, silicon, and phosphorus), may contribute towards increasing soil pH and aiding nutrient availability (Agbeshie et al., 2022; Bodí et al., 2014). This study investigates the effects of prescribed fire on SOC stocks and sequestration (20 years), TotN, and stable carbon fractions (refractory OM & BC) in South African mesic grasslands. We hypothesise that fire frequency drives shifts in soil carbon sequestration, stability and pH, with increased fire frequency enhancing surface SOC retention but reducing refractory OM and BC stabilisation in deeper soil layers.

Methods

The Ukulinga Grassland Fire Experiment (UGFE), at the University of KwaZulu-Natal Research Farm in Pietermaritzburg South Africa (-29.667° S, 30.399° E; altitude 843 m), examines the effects of prescribed burning on subtropical mesic grasslands under summer-dominant rainfall. Soils at the site are sandy clay loam, with an orthic A over a soft plinthic B horizon (Soil Classification Working group, 1991), and the mean annual rainfall is 790 mm, ~95% occurring in summer (November to February). Mean temperatures range from 26.4°C in February to 8.8°C in July (Fynn et al., 2003). Vegetation is classified as KwaZulu-Natal Hinterland Thornveld, dominated by native C4 grasses (Mucina & Rutherford, 2006).

The UGFE, initiated by J.D. Scott in 1950 to study historically prescribed burning regimes, was established with a randomized split-plot design, incorporating three replications for each treatment on plots measuring

18.3 × 13.7 m. The UGFE has been entirely excluded from domestic livestock and large wild ungulate grazing regimes. For this study, 9 burn treatments within this experiment, namely annual, biennial, and triennial burning in winter, spring, or autumn, as well as fire exclusion, were utilised. Burns were conducted according to seasonal protocols: spring burns followed the first 12.5 mm of rainfall (usually within September), while winter burns were conducted in early August. The experimental plots in this study were consistently burned in accordance with the established UGFE protocol throughout the duration of the experiment, with no deviations in application and no impact from wildfires. Soil organic carbon (SOC) stocks were assessed at a second time point (2021) and compared to those measured 20 years earlier in a study by Fynn et al. (2003). The rate of carbon sequestration over this 20-year period was then estimated.

To assess prescribed fire history on grassland SOC accumulation, soils were collected in May 2021 using a 2.8 cm soil corer. Four random cores per plot were sampled to a depth of 30 cm, segmented into 5 cm increments and composited. Samples were dried (65°C, 48 hours), homogenised, sieved to 0.5 mm, and analysed for total SOC and nitrogen using a Leco TruMac CNS analyser. Organic carbon and nitrogen concentrations were calculated and converted to SOC and TotN stocks (Mg ha⁻¹) per treatment (FAO, 2020). Recalcitrant carbon fractions (ROC and BC) were quantified using a thermogravimetric analyser (TGA) under a nitrogen atmosphere, with ROC recorded between 475–550°C and BC between 550–650°C.

Hierarchical linear mixed models assessed the effects of fire frequency, season of prescribed burns, and soil depth on SOC stocks (2021), SOC sequestration (20yrs), TotN, C:N ratios, and carbon fractions. Plots were treated as random effects to account for variability between them, and fixed effects included nested interactions between fire treatments and soil depth. Diagnostic checks confirmed model assumptions (normality, equal variance, linearity, independence, & overall fit of the model) were met, and post hoc Tukey HSD tests evaluated significant differences between treatments. Pearson's correlation assessed the relationship between soil pH and BC levels, while one-way ANOVAs examined acid saturation and fire treatment effects. Statistical analyses were conducted in R (R Core Team, 2023), using standard packages for data processing and visualisation.

Results

Total Carbon, Nitrogen, and Refractory Organic Carbon Status

Soil organic carbon (SOC) and total nitrogen (TotN) stocks declined significantly with increasing soil depth (SOC: $\beta = -0.396$, $p = 0.02$; TotN: $\beta = -0.046$, $p < 0.001$, Figure 1). SOC stocks were highest in annual winter burns ($\beta = 0.995$, $p < 0.001$) and fire exclusion treatments relative to SOC stocks in the biennial and triennial burn treatments in autumn and winter ($p < 0.01$). Depth had a marginally positive effect on C:N ratios ($\beta = 0.003$, $p = 0.05$), with fire exclusion significantly reducing C:N ratios ($\beta = -4.310$, $p < 0.001$).

Refractory organic carbon (ROC) concentrations were highest in the top 5 cm of soil (19.62 ± 0.929 g/kg) and declined significantly with depth ($p < 0.001$). Burning treatments did not affect ROC levels, while black carbon (BC) remained stable across soil depths (1.87 ± 0.180 g/kg). Grasslands excluded from fire exhibited the greatest BC concentration (10.27 ± 2.141 g/kg), relative to annual and biennial burns BC quantities. A significant negative correlation between BC and soil pH ($r = -0.384$, $p < 0.001$) revealed that acidified soils retained more BC.

Carbon Sequestration and Fire Frequency

SOC sequestration over 20 years varied by fire treatment and depth, with triennial burns showing negative sequestration in the 5–10 cm soil layer (winter: -0.16 ± 2.0 Mg C/ha; spring: -0.46 ± 3.42 Mg C/ha; autumn: -1.03 ± 2.23 Mg C/ha). In contrast, annual winter burns exhibited the highest SOC sequestration (1.1 ± 1.0

Mg C/ha) in the top 5 cm. Depth was the strongest predictor of changes in SOC sequestration with SOC decreasing with increasing depth ($p = 0.001$).

Soil Acidification and Fire Exclusion

Plots with fire exclusion and triennial treatments had significantly lower pH than more regularly burned plots ($p < 0.001$, $F_{9,80} = 4.67$). Soils excluded from burning had the lowest pH, with a mean of 4.2 ± 0.3 , while annual winter burns had near-neutral pH levels (pH 6.1 ± 0.4). Acid saturation was notably greater in unburnt soils and those with extended burn intervals, indicating maintained acidification with reduced fire frequency.

Black carbon (BC) accumulation was highest in fire-excluded plots (10.27 ± 2.141 g/kg), followed by triennial winter burns (6.13 ± 0.474 g/kg). BC content was negatively correlated with pH ($r = -0.384$, $p < 0.001$), with higher BC concentrations observed in plots with lower pH values.

Discussion [Conclusions/Implications]

The significant declines in SOC and TotN stocks with increasing soil depth highlight that the greatest concentrations of SOC and TotN are found in the topsoil, emphasizing the importance of protecting this layer to prevent losses. The greatest SOC in the top 5 cm of soil under annual and biennial burns, particularly in spring, suggests this layer has the greatest capacity for SOC sequestration, supporting findings from similar studies that link moderate fire temperatures with enhanced microbial activity and nutrient cycling (Fynn et al., 2003; Ohrtman et al., 2012).

Low levels of SOC sequestration (measured within a 20-year timeframe) below 5 cm under Triennial burns suggest losses, likely driven by biomass accumulation and shifts in lignin composition, resulting in incomplete combustion. These results challenge the assumption that SOC stocks stabilise within 20 years.

While Fire exclusion appeared to promote BC accumulation, it also appeared in acid conditions, possibly inhibiting nutrient cycling. This is consistent with studies linking fire suppression to the buildup of lignified biomass and coarse BC particles, which stabilise in acidic conditions but limit overall carbon turnover (Agbeshie et al., 2022; Docherty et al., 2012), akin to the 'use it or lose it' principle. The negative correlation between BC and soil pH suggests that acidic soils favour BC retention but hinder the decomposition of organic material, emphasizing the dual role of fire in stabilising and mobilising carbon fractions. The persistence of SOC and recalcitrant carbon forms such as ROC and BC in deeper soil horizons remains an area for further study. These stable fractions, influenced by ash deposition and fire-induced changes in soil, play a vital role in long-term carbon storage and climate mitigation (Lorenz & Lal, 2005).

These results suggest that the interval of prescribed burns must balance carbon sequestration objectives with the maintenance of soil fertility and grassland functionality. Prescribed fire in subtropical grasslands with summer-dominated rainfall, particularly in spring, appears to sustain mesic grasslands as carbon sinks. Annual and biennial burns, particularly in spring, optimise carbon sequestration and nutrient cycling while mitigating soil acidification.

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