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TECHNICAL NOTE

Pedology

Fire exclusion reduces A-horizon thickness in a long-term prescribed fire experiment in Spodosols of northern Florida, USA

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Abstract

Fire influences soils, but it is difficult to attribute long-term changes in soils to fire, given the short duration, and irregular return interval of most fires. Prescribed fire, in which landscapes are intentionally burned, offer some experimental control, but study sites where prescribed fire has been applied systematically over decades are rare. We had the opportunity to investigate the effects of prescribed fire on soil horizon thickness in Spodosols from a long-term study in northern Florida, USA, in which three prescribed fire frequency treatments (1, 2, or 4 years) and an unburned control have been continuously maintained in replicated experimental plots for the last 60 years. We found that the thickness of the A horizon in these soils was diminished in the unburned control plots, relative to those in plots receiving regular fire treatments. While conclusions based on one morphological measurement, thickness, certainly have limitations, drivers of this peculiar finding may have implications for carbon storage and vulnerability in these fire-maintained landscapes.

1 | INTRODUCTION

Fire impacts soils, either directly through physical and chemical changes associated with combustion and heating (Santín & Doerr, 2016) or indirectly through changes to biota and organic matter that then lead to changes in soil (Gagnon et al., 2015; Pressler et al., 2019). This understanding has led to the suggestion that fire might be considered as an additional soil-forming factor (Certini, 2014), but it is difficult to define fire as a perpetual pedogenic force in the way that other factors (e.g., climate, relief) are, given fire's discrete and often irregular occurrence. Fire "regime," defined as the typical characteristics (e.g., intensity, frequency, severity) of multiple fires (McLauchlan et al., 2020), may be a more continuous property comparable to other soil-forming factors, but the practical limitations required to manipulate fire regime prevent its effect on soil from being well-studied.

Fire-adapted ecosystems that are maintained by the application of prescribed fire at regular intervals offer the opportunity to study fire more as a continuous force than a discrete event. Prescribed fires are intentionally set by land managers to achieve multiple objectives (e.g., decrease fuel loadings, improve wildlife habitat, maintain fire-adapted ecosystems; Waldrop & Goodrick, 2012). Most research on prescribed fire effects on soil has focused on soil carbon and nutrient cycling, with different patterns detected (Butnor et al., 2020 and references therein), suggesting site/fire-specific effects. Replicated, experimental study sites in which prescribed fire has been applied in a regular, systematic fashion continually for more than a decade are rare. As such, there are few examples of studies that measure multi-decade, continually applied prescribed fire effects on soil properties.

We had an opportunity to provide information on one soil morphological property, horizon thickness, at a long-term prescribed fire study in northern Florida, USA, where treatments (prescribed fire applied every 1, 2, or 4 years, and an unburned control) have been continually maintained for over 60 years. As a part of a larger soil organic matter and microbial ecology study at this site (S. Fox, 2022), we sampled soils and recorded horizon thicknesses. Upon analysis of the thickness data, we found an interesting pattern, and report it here.

Core ideas

- Fire impacts soils, but its temporary and irregular occurrence presents challenges to researchers.
- Prescribed fire, where it is applied systematically, offers an opportunity to understand fire effects on soils.
- At a prescribed fire study that has been maintained for 60 years, we measured mineral soil horizon thicknesses.
- Thickness of the A horizon was diminished by an average of 2.6 cm in unburned controls compared to burned plots.

2 | METHODS

Sampling for this study was conducted at the Olustee Experimental Forest, a part of Osceola National Forest in northern Florida (30°14′04.8″ N, 82°24′45.3″W). The area has a humid subtropical climate (mean annual temperature: 19.6°C, mean annual precipitation: 137.1 cm; https://www.ncei.noaa.gov/access/us-climate-normals). Soils of the area are Spodosols (Sandy, siliceous, thermic Ultic Alaquods) and are mapped as Sapelo fine sands (Soil Survey Staff, 2022).

In 1958, a prescribed fire study was initiated on a 20.8 ha tract of long-leaf pine (*Pinus palustris* Mill.) forest on the Olustee Experimental Forest in which four fire frequency treatments (burned every 1, 2, 4 years or unburned) were randomly assigned to 24 rectangular plots (0.8 ha each) that were established within six parallel blocks along a slight moisture gradient (Figure 1). Plots are separated from each other only by fire lines (approximately 4 m wide), and the study site is low elevation (51 m) and very flat (slope <1%; i.e., little to no difference in landscape position, slope, aspect, erosion, denudation, or lithology between plots). Before the study began, the forest was maintained by fires occurring every 5–6 years (personal communication, D. Wade). Plot treatments have been continually applied since the study's inception. Tree communities inside the plots remain dominated by long-leaf pine (though hardwoods have encroached in the midstory of unburned plots). The understory of the plots is dominated by shrubs, particularly saw palmetto (*Serenoa repens* Bartr.) and inkberry [*Ilex glabra* (L.) Gray], and many species of herbaceous plants (Glitzenstein et al., 2003).

Soils were sampled (January–March 2018) by removing the organic horizon (if present; distinguished from A horizons by the presence of fragmented litter and humus), and then using an auger to remove mineral soil and place it into a polyvinyl chloride trough (Figure 2). Then, the collected mineral soil was determined to be part of the A, E, or Bh horizon based on visual comparisons of color. In these sandy soils, color changes between horizons are stark (Figure 2). Soil A horizons are characterized by the presence of bits of charcoal and organic matter, giving the soil a gray-dark gray appearance (hue: 7.5 YR, value: 5, chroma: 1; Munsell Color, 2009). Soil E horizons are very pale-yellow sand (hue: 2.5Y, value: 8.5–9.5, chroma: 2), having had organic matter leached out, and into the spodic Bh horizon, giving that horizon a brown appearance (hue: 7.5YR; value: 4; chroma: 4). Once horizons were defined, we recorded the thickness of the A and E horizons, and depth to the top boundary of the Bh horizon. This process took place until the top 10 cm of the Bh horizon was collected. In each plot, samples were taken 3 m to the south of 7 or 10 randomly selected (but avoiding plot edges) dominant long leaf pine stems. Mean thickness values of the A and E horizons and mean depth values to the Bh horizon were composited across these samples by plot, and the calculated thickness/depth per plot was used in analyses.

Thicknesses of the A and E horizons, and depths to the Bh horizon ($n = 6$), were analyzed using a linear mixed model (all analyses conducted using R; R Core Team, 2022) in which fire frequency was treated as a fixed effect and block was treated as a random intercept (lmer() function in lme4 package; Bates et al., 2015). Significance was assessed using the Wald chi-square test [Anova() function in car package; J. Fox & Weisberg, 2019]. Model assumptions were checked visually and found to be upheld (Stowell & Pace, 2014). We performed post hoc pairwise comparisons of group means using estimated marginal means with the Tukey adjustment for multiple comparisons (emmeans() function in emmeans package; Lenth, 2022). Figure 3 was created using the ggplot package (Wickham, 2016) with Munsell colors from the AQP package (Beaudette et al., 2022).

3 | RESULTS

Fire frequency significantly influenced A-horizon thickness ($\chi^2 = 27.3$, df = 3, $p < 0.001$). Post hoc comparisons revealed that A-horizon thickness was diminished in the unburned plots relative to plots in the three burned treatments [$t = -3.9$ (1 year), $t = -4.4$ (2 year), $t = -4.5$ (4 year), df = 15, $p < 0.01$], which did not differ from each other ($p > 0.05$). On average,

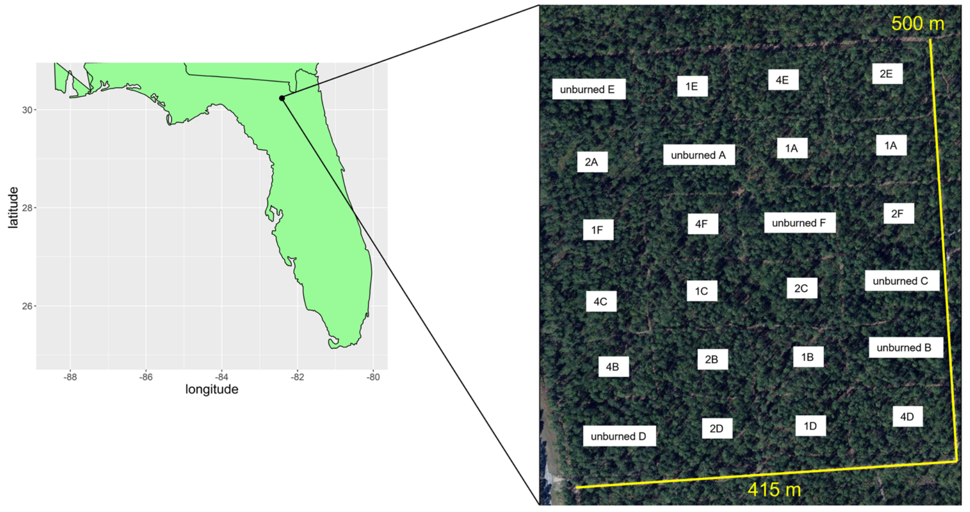

FIGURE 1 The long-term fire study at the Olustee Experimental Forest in Florida, USA. Twenty-four plots were established in 1958, with four treatments (burn every 1, 2, 4 years, and unburned controls) replicated across six blocks. Plot labels indicate treatments (numerals are fire return interval in years, letters are block assignments)

FIGURE 2 A photograph of one of the soil samples taken from the long-term prescribed fire study at the Olustee Experimental Forest in Florida, USA, showing the A, E, and Bh horizons as delineated by color

the A horizons in the burned plots were 2.6 cm thicker than in the unburned plots (Figure 3). We did not find fire frequency treatment effects on E horizon thickness (χ^2 = 3.2, df = 3, p = 0.37) or depth to the Bh horizon (χ^2 = 7.1, df = 3, p = 0.07).

4 | DISCUSSION

Our results show that unburned plots have A horizons that are less thick than those that have experienced 60 years of continuously maintained prescribed fire treatments. This indicates that morphological features can be altered by fire, or perhaps fire regime, suggesting that fire may act as a soil-forming factor for morphological properties. The findings of Takahashi et al. (1994), which showed that pyrolyzed carbon contributed to the melanic epipedon in Andisols of California, support this conclusion. More work is required at different locations, studying other soil characteristics to conclude whether fire, or fire regime, can be included as an additional soil-forming factor.

The changes to A-horizon thickness that we ascribe to fire could be driven by two (or more) mechanisms. First, changes to inputs that are driven by fire may influence horizon thickness. While we did not measure O horizons in this study, other studies have found that O horizons are thicker in unburned areas than burned areas (summarized in Callaham et al., 2012). A previous study at the Olustee Experimental Forest (DiCosty et al., 2006) found that organic matter was reduced in A horizon soils of unburned plots, compared to burned plots. This suggests that organic matter may be held in the O horizon in unburned plots, limiting inputs to the A

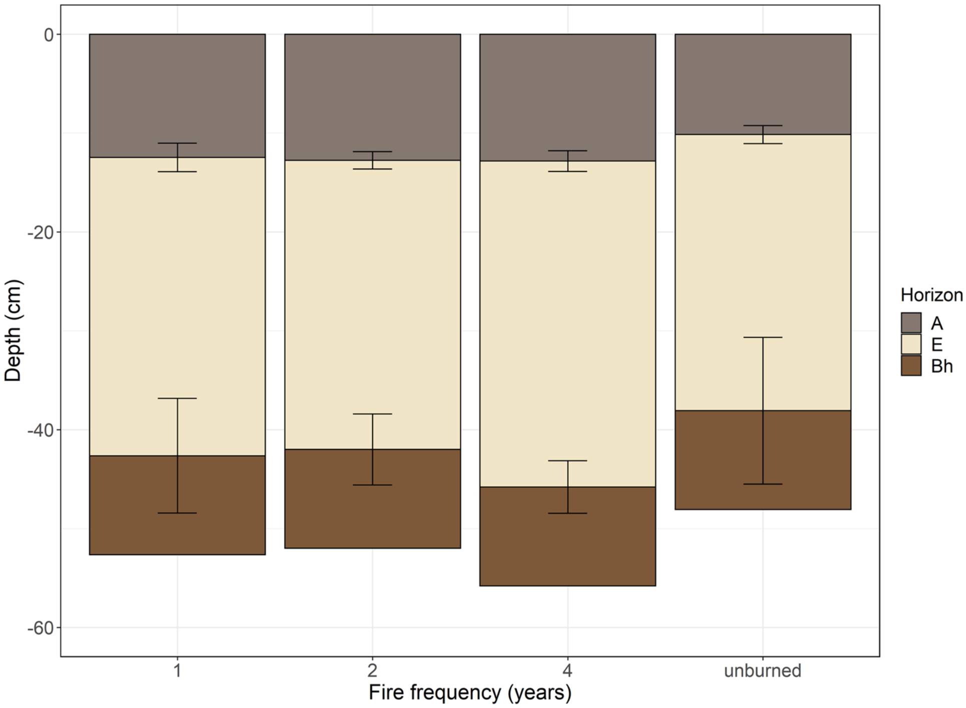

FIGURE 3 Mean (±SD) depths of mineral soil horizons at the Olustee Experimental Forest after 60 years of continually maintained prescribed fire treatments and unburned controls

horizon, and thereby decreasing its thickness over time. Second, fire may cause changes to bulk density in burned plots through the inputs of ash that cause A horizons there to be less dense, thereby influencing horizon thickness. Massman and Frank (2006) found no impact of prescribed fire on soil bulk density, but the results may be different at longer time intervals of study or in other soil types. Supporting evidence for each of these mechanisms comes from the data used in DiCosty et al. (2006), showing higher carbon content and lower bulk density in plots that burned yearly compared to unburned plots (Table S1), suggesting the two proposed mechanisms may co-occur. In either case, given the lack of non-treatment differences between plots, we conclude that the presence (or absence) of fire is the likely cause of differences in A-horizon thickness measurements.

This study was not preplanned, but rather this finding was noted as a part of a larger study. As such, there is an important limitation to our findings that should be acknowledged. Our results are of one morphological characteristic, horizon thickness, which was based on soil color. Other horizon delineations based on chemical or physical properties may provide different results. While acknowledging this limitation, we speculate, that if the absence of fire diminishes the A horizon in these fire-maintained forests (and instead organic matter is held in the O horizon), there may be important implications for the vulnerability of carbon to combustion in the event of burning in long-unburned forests, given the heightened physical protection offered to carbon stored in the A horizon, compared to that in the O-horizon.

AUTHOR CONTRIBUTIONS

Melanie K. Taylor: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing – original draft; writing – review & editing. **Dexter J. Strother**: Methodology; writing – review & editing. **Mac A. Callaham Jr**: Conceptualization; methodology; project administration; supervision; writing – review & editing.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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