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Mineral Soil Chemical Properties as Influenced by Long-Term Use of Prescribed Fire with Differing Frequencies in a Southeastern Coastal Plain Pine Forest

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Abstract: Recent studies suggest increased fire frequency may impair soil chemistry, but few studies have examined long-term effects of repeated, frequent prescribed fires on forest soil properties in the southeastern Coastal Plain, USA. In this study, forest soil chemistry at the 0–10 and 10–20 cm mineral soil depths of sandy surface horizons (Entisols and Spodosols) were compared among units burned 0, 4, 6, and 8 times between 2004 and 2015 and 0 and 20 times between 1978 and 2015 in a longleaf (*Pinus palustris* Mill.)–loblolly (*Pinus taeda* L.) pine savanna at the Tom Yawkey Wildlife Center (Georgetown, SC, USA). At the 0–10 cm soil depth, soil pH (p = 0.00), sulfur (p = 0.01), calcium (p = 0.01), iron ($p < 0.01$), manganese ($p < 0.01$), and aluminum (p = 0.02) treatment means differed (2004–2015). Calcium and manganese displayed positive, significant relationships and sulfur displayed a negative, significant relationship with increasing fire frequency ($p < 0.05$). However, correlation of these relationships was low ($r^2 \leq 0.23$). Using linear contrasts to compare the mean of all fire treatments (20 fires from 1978 to 2015) to the mean of the unburned compartment, sulfur (p = 0.01) and iron ($p < 0.01$) were less in soils from the burned compartments. At the 10–20 cm soil depth, soil pH (p = 0.01), manganese (p = 0.04), phosphorus (p = 0.01), potassium (p = 0.02), and iron ($p < 0.01$) treatment means differed (2004–2015). Potassium displayed a negative, significant relationship and soil pH displayed a positive, significant relationship with increasing fire frequency ($p < 0.05$). Correlation of these relationships was low ($r^2 \leq 0.16$), however. Using linear contrasts to compare the mean of all fire treatments (20 fires from 1978 to 2015) to the unburned compartment, potassium (p = 0.00) and iron ($p < 0.01$) were less in soils from burned compartments. These results are inconsistent with studies suggesting that forest soil chemistry is substantially altered by increased fire frequency and support other studies from this region that have documented minimal or temporary soil chemical changes associated with frequent prescribed fires.

Keywords: forest soils; wildland fire; prescribed fire; carbon; nitrogen; calcium

1. Introduction

Fire has been a formative force for forest vegetation and soil properties in many ecosystems for millennia [1–3]. Therefore, numerous ecosystem properties and processes are influenced by the time since last fire, or fire return interval [4,5]. In some landscapes, such as the spruce-fir forests of the Adirondack Mountains [6], historic fire return intervals may have spanned several decades prior to 1850 [3]. Other locations, such as the southeastern Coastal Plain, are hypothesized to have fire return intervals of two years or less [3] due to both natural and anthropogenic ignitions [7,8].

The historic precedent and cultural acceptance of fire in some southern U.S. locations favored the continued use of fire, despite broad-scale fire exclusion throughout the majority of the twentieth century across many regions of the United States [8,9]. Forest managers across the southeastern U.S. have relied upon prescribed fires to accomplish multiple objectives including wildfire hazard reduction, wildlife habitat management, forest pest and disease reduction, and ecosystem restoration [2]. This use of prescribed fire and its subsequent effects on soils and other important ecosystem properties contrasts markedly to wildfires and their associated effects [10,11]. Wildfires are typified by high fire intensity and severity caused by ignitions in long-unburned areas with heavy fuel loads, whereas frequent, prescribed fires of the southeastern Coastal Plain are generally characterized by low intensity and severity [5,12–15]

Wildfire effects on soils in long-unburned forests have been widely studied and investigated [16–18]. Studies across multiple continents indicate that potential outcomes of high-severity wildfires include: (1) increased potential for soil erosion and formation of hydrophobic soils, (2) alteration of soil aggregates, and (3) volatilization of soil organic constituents due to duff consumption and soil heating [19,20]. Prescribed fire effects on soils have also been well documented around the globe but the results are highly variable. Gains, losses, and non-significant alterations to many soil biological, chemical, and physical properties are documented in the literature [21,22]. Prescribed fire effects appear to be strongly influenced by multiple factors including geographic location and the associated vegetative community, post-fire sampling period and sampling parameters (such as days since precipitation, forest floor moisture, etc.), fire frequency, seasonality, laboratory analysis methods, and other variables [21–25]. Furthermore, studies investigating prescribed fire effects are dominated by short-term, post-fire soil responses in most regions [26].

Recently Pellegrini et al. [27] suggested that increased fire frequency may have deleterious effects on forest carbon (C) and nitrogen (N) based upon an international meta-analysis of 48 sites worldwide. In their synthesis, Carter and Foster [21] also cautioned that long-term fire use may impair long-term forest productivity in pine forests of the southern United States. To our knowledge, few prescribed fire studies have investigated the long-term effects of frequent prescribed fires on soil properties and processes of pine forests in the southeastern Coastal Plain. McKee [12] determined that long-term burning had no undermining effects on surface mineral soil (0–16 cm depth) organic matter (OM) or total N in three Flatwoods/Coastal Plain locations in Alabama (longleaf pine (*Pinus palustris* Mill.); Ultisols), Florida (longleaf and slash (*Pinus elliottii* Engelm.) pines; Spodosols), and South Carolina (loblolly pine (*Pinus taeda* L.); Ultisols). At an additional location in Louisiana (longleaf pine; Alfisols), McKee noted decreases in N and OM at the 0–5 cm depth. At all four locations, phosphorus (P) increased with burning in surface mineral soils (0–5 cm depth in Alabama and Florida and 0–8 cm depth in South Carolina and Louisiana) and calcium (Ca) exhibited increases in surface mineral soils in Alabama, Florida, and South Carolina. Without burning, McKee suggested that Ca immobilization was prevalent in the O Horizon, which could lead to Ca deficits in the mineral soil. In another loblolly–longleaf pine forest in the South Carolina Coastal Plain, Binkley et al. [28] found that surface mineral soil (0–20 cm; Ultisol) C and N were not altered as a result of long-term burning. Boyer and Miller [29] also found that mineral soil N (0–15 cm; Ultisol) was not significantly altered by site preparation burning of a longleaf pine forest in the Alabama Coastal Plain. Recently, Godwin et al. [30] reported that long-term annual and biennial burning in a mixed pine (shortleaf (*Pinus echinata* Mill.)–loblolly–longleaf; Ultisols) forest in Florida resulted in significant increases of surface soil (0–10 cm) C and magnesium (Mg). Though not significantly different than unburned soils, N, P, Ca, potassium (K), and pH also increased in this study.

In light of the paucity of information regarding fire and its potential, long-term impacts on southeastern Coastal Plain soils, despite the widespread use of prescribed fire in the region [31], we evaluated the effects of frequent prescribed fire for forest soil chemistry (0–10 and 10–20 cm soil depths; Spodosols and Entisols) in a longleaf pine-dominated forest located in the southeastern Coastal Plain near Georgetown, SC, USA. The burn history at this location offered a unique opportunity to investigate the potential impacts of increasing, short-term fire frequency from 2004 to 2015 and the long-term effects of 20 fires from 1978 to 2015. We used the long-term, soils-related burning literature for this region (cited above) to inform our hypotheses regarding the correlation of increasing short-term frequency and long-term effects of prescribed fire on soil properties. Hypotheses were (1) increased short-term fire frequency from 2004 to 2015 would be poorly correlated with soil chemical properties and (2) most soil properties would not be altered by long-term prescribed fire use from 1978 to 2015 (20 fires in 37 years), with the exception of Ca, pH, and P, which would increase at the 0–10 cm depth. Examined soil properties and characteristics included aluminum (Al), boron (B), C, Ca, copper (Cu), iron (Fe), Mg, manganese (Mn), N, OM, P, K, soluble sulfur (S), sodium (Na), zinc (Zn), soil pH, and total cation exchange capacity (CEC).

2. Materials and Methods

2.1. Study Site

This study was conducted at the Tom Yawkey Wildlife Center in Georgetown, SC, USA (hereafter referred to only as Yawkey) (33.23° N, 79.22° W) (Figure 1). Mean temperature in this area was 18.3 °C (mean range: 12.1 °C (low)–24.6 °C (high)) and mean annual precipitation was 143 cm. Longleaf pine was the dominant tree species present in the overstory, followed by loblolly pine, turkey oak (*Quercus laevis* Walter), and sweetgum (*Liquidambar styraciflua* L.). Wiregrass (*Aristida stricta* Michx.) is not present as a groundcover vegetative species; bracken fern (*Pteridium aquilinum* (L.) Kuhn) is the dominant groundcover species throughout the property. Provision and maintenance of red-cockaded woodpecker (*Leuconotopicus borealis* Vieillot) habitat is the primary management objective at Yawkey and dormant season prescribed burning, typically in February or March, is the primary management tool used to support this objective. Records on prescribed fire implementation have been maintained on the property since 1978, following acquisition by the South Carolina Department of Natural Resources (SCDNR) [32]. One 6.47 ha (16 acre) forested compartment on the property has not been burned during this time period. The majority of the management units on the property were burned repeatedly, in some cases up to 20 times, from 1978 to 2015. For the purposes of this study, we additionally dissected burn history to include the number of burns from 2004 to 2015. Representative images of both the long-term unburned and regularly burned portions of Yawkey are provided (Figure 2).

Mineral soils from 9 compartments at Yawkey were sampled in March 2015 (Figure 1). Most locations on this property lack a significant duff layer (Oe + Oa Horizons) due to the frequency of burning. Therefore, that layer was not included in our sampling and subsequent analyses. Eight of the 9 compartments were approximately 1–2 ha (2–5 acres) in size and were randomly selected for evaluation. Each of these compartments was burned 20 times from 1978 to 2015 and had previously been burned in 2014. From 2004 to 2015, 2 compartments were burned 4 times, 3 compartments were burned 6 times, and 3 compartments were burned 8 times. The long-term unburned (0 fires from 1978 to 2015) compartment was also sampled in March 2015.

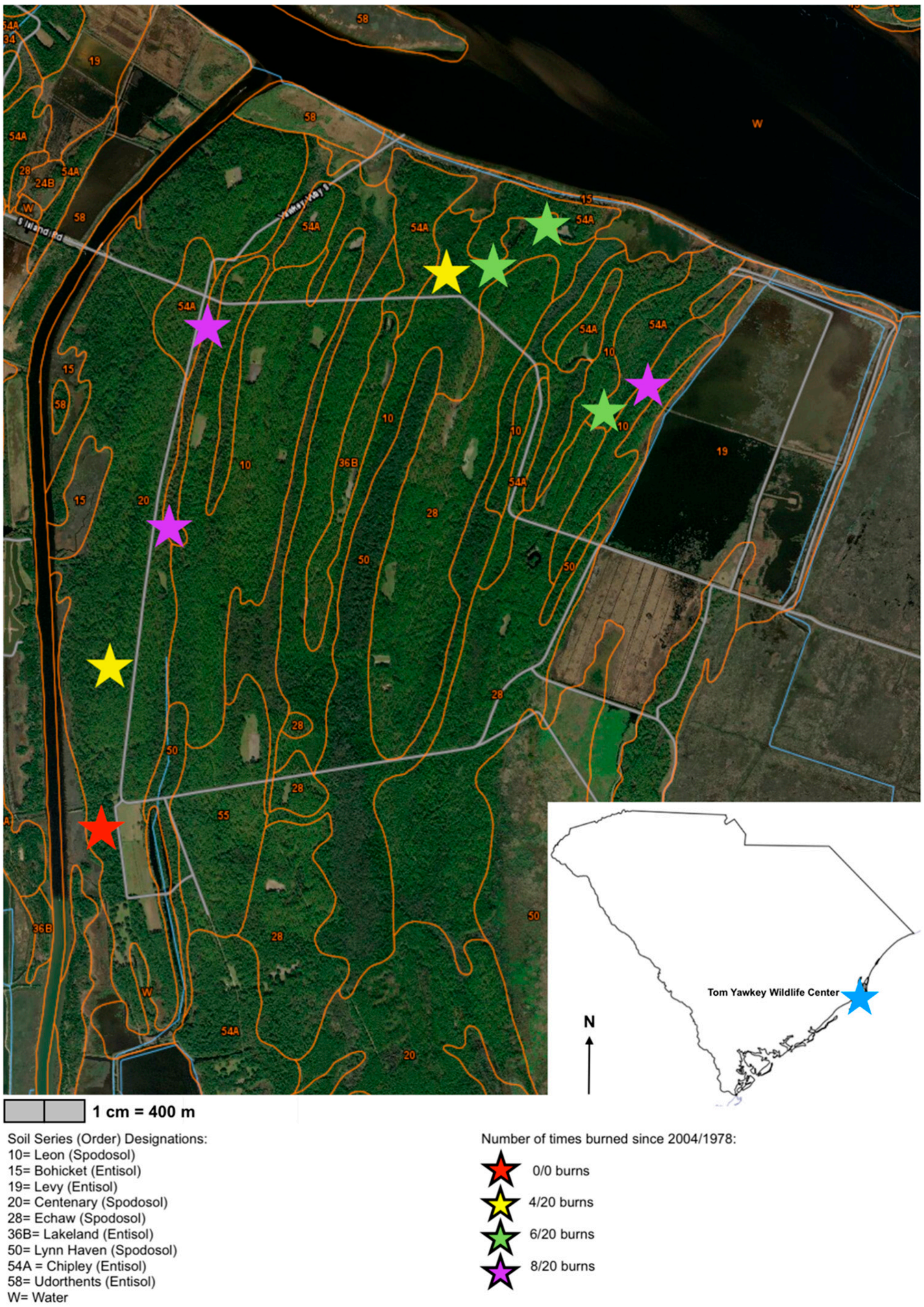

Figure 1. Location of the Tom Yawkey Wildlife Center, Georgetown, SC, USA (33.23° N, −79.22° W) and the spatial orientation of soil sampling transects (every 50 m), associated soil series designations, and the number of times burned since 2004/1978.

(a)

(b)

Figure 2. Representative photographs depicting conditions of the (**a**) long-term unburned compartment and (**b**) regularly burned compartments of the Tom Yawkey Wildlife Center, Georgetown, SC, USA in March 2015. The long-term unburned compartment was characterized by closed canopy conditions, higher stand density, and higher forest floor depth and mass. The regularly burned compartments were characterized by open canopy conditions, lower stand density, and lower forest floor depth and mass.

2.2. Soil Sampling

Soils were collected with an Oakfield Model H soil probe (2.06 cm inner diameter) and placed in paper bags for the 0–10 and 10–20 cm soil depths (Figure 3). Sampling locations were established approximately 50 m apart along linear transects within each of the 9 treatment units. At each sampling location, 3 separate samples from each depth were collected approximately 1 m apart and placed into one bag for each depth. This sampling protocol resulted in the following sample sizes for each soil depth from 2004 to 2015: unburned (n = 5), burned 4 times (n = 11), burned 6 times (n = 15), burned 8 times (n = 15). Using these designations for 1978–2015, the sample sizes equaled: unburned (n = 5) and burned 20 times (n = 41).

Figure 3. Typical abbreviated soil profile consisting of O, A, E1, and E2 for a Spodosol obtained using the Oakfield Model H soil probe at the Tom Yawkey Wildlife Center, Georgetown, SC, USA. Soil order was identified using the USDA Natural Resources Conservation Service Web Soil Survey. Due to frequent burning, Oe and Oa Horizon materials were not readily present for the majority of our samples and were therefore not included in our analyses of mineral soil properties.

Soils on these sites were comprised of similar sandy surface horizons to the 20 cm soil depth. Sampled soil series included one Entisol, Chipley (Thermic, coated Aquic Quartzipsamments), and four Spodosols, Centenary (Sandy, siliceous, thermic Entic Grossarenic Alorthods), Echaw (Sandy, siliceous, thermic Typic Alaquods), Lynn Haven (Sandy, siliceous, thermic Typic Alaquods), and Leon (Sandy, siliceous, thermic Aeric Alaquods). Statistical analyses based upon soil series and order were conducted but proved nonsignificant; therefore, these designations are not discussed in the results.

2.3. Soil Processing

Soil samples for each soil depth were oven-dried at 70 °C for at least 48 h and sieved at 2 mm. Laboratory analyses were contracted to Brookside Laboratories in New Bremen, OH, USA, and approximately 30 g of soil were utilized to determine concentrations of the following chemical elements and properties: Al, B, C, Ca, Cu, Fe, Mg, Mn, N, OM, P, K, soluble S, Zn, soil pH, and total CEC. Carbon and N were determined by dry combustion of samples and subsequent measurements conducted with the Perkin-Elmer 2400 Series CHNS/O Analyzer [33]. The additional element concentrations were determined using Mehlich III methodology [34] and subsequent analysis for each element of interest by ICP-Optical Emission Spectrometry [35]. Organic matter was determined by loss of ignition at 360 °C [36]. Soil pH was determined using a 1:1 soil-to-water solution [37]. Total CEC was determined by summation [38].

2.4. Statistical Analyses

Analyses of variance (ANOVA) were conducted to determine differences between mean values for soil chemical properties within the four fire frequency treatments from 2004 to 2015 at both soil depths using JMP® (Version 12, SAS Institute Inc., Cary, NC, USA). Least square means were determined and a Tukey's test was used to separate means when differences from 2004 to 2015 were detected. Linear regressions were performed to determine significant relationships and correlations for soil chemical properties and fire frequency from 2004 to 2015. Linear contrasts were conducted to compare the mean of all prescribed fire treatments (those compartments burned from 1978 to 2015) with the unburned treatment. Differences were declared statistically significant at $\alpha = 0.05$.

3. Results

3.1. Soil Depth 0–10 cm

Significance of differences between the treatment means at the 0–10 cm soil depth for 0, 4, 6, and 8 burns from 2004 to 2015 were determined for the following variables: Al ($p = 0.02$), Ca ($p < 0.01$), Mn ($p < 0.01$), S ($p = 0.01$), Fe ($p < 0.01$), soil pH ($p = 0.00$) (Table 1). Soil pH, Ca, and Mn were highest at locations burned 8 times from 2004 to 2015, but were only significantly different from the unburned compartment for Ca. Aluminum was highest at locations burned 4 times, but was only significantly different from locations burned 6 times. Sulfur and Fe were highest on the unburned compartment, but only Fe displayed significant values above all of the burned treatments. Calcium ($p = 0.01$), Mn ($p = 0.00$), and S ($p = 0.01$) displayed significant relationships with fire frequency (Table 2). Both Ca and Mn increased with increasing fire frequency and S decreased with increasing fire frequency. The strength of these relationships was low, however, as all $r^2 \leq 0.23$. Using linear contrasts to compare the mean of all of the burned compartments from 1978 to 2015 to the mean of the unburned compartment for each of the variables, Fe ($p < 0.01$) and S ($p = 0.01$) were the only variables that indicated a significant reduction as a result of fire inclusion from 1978 to 2015. The remaining comparisons yielded $p > 0.05$ (Table 1).

Table 1. Soil chemical property means (±standard error) at the 0–10 cm soil depth based upon fire frequency from 2004 to 2015 and linear contrast results for fire inclusion from 1978 to 2015 at the Tom Yawkey Wildlife Center, Georgetown, SC, USA. Means with different lowercase letters are statistically different at $\alpha = 0.05$.

Soil Property (0–10 cm) [1]	Means ± Standard Error for Fire Treatments, 2004–2015						Burned vs. Unburned Contrast, 1978–2015	
	0 Burns $n = 5$	4 Burns $n = 11$	6 Burns $n = 15$	8 Burns $n = 15$	ANOVA Stat	ANOVA p-Value	Contrast Stat	Contrast p-Value
Al	699 ± 110ab	708 ± 111a	426 ± 47b	581 ± 39ab	3.56	0.02	1.26	0.27
B	0.38 ± 0.02	0.35 ± 0.05	0.33 ± 0.06	0.34 ± 0.03	0.11	0.95	0.19	0.67

Table 1. *Cont.*

Soil Property (0–10 cm) [1]	Means ± Standard Error for Fire Treatments, 2004–2015						Burned vs. Unburned Contrast, 1978–2015	
	0 Burns *n* = 5	4 Burns *n* = 11	6 Burns *n* = 15	8 Burns *n* = 15	ANOVA Stat	ANOVA *p*-Value	Contrast Stat	Contrast *p*-Value
Ca	140 ± 16b	199 ± 30ab	173 ± 13b	282 ± 33a	4.69	0.01	3.08	0.09
Cu	0.13 ± 0.03	0.20 ± 0.02	0.13 ± 0.02	0.20 ± 0.03	2.22	0.10	1.23	0.27
Fe	296 ± 14a	155 ± 16b	105 ± 12c	198 ± 8b	27.88	<0.001	48.49	<0.001
Mg	31.4 ± 2.2	40.6 ± 4.5	43.4 ± 3.7	37.9 ± 4.0	0.99	0.40	1.86	0.18
Mn	1.48 ± 0.45ab	1.20 ± 0.21b	1.24 ± 0.17b	3.65 ± 0.59a	9.27	<0.001	0.65	0.43
P	9.60 ± 0.81	13.18 ± 1.16	12.60 ± 0.60	11.20 ± 1.01	1.83	0.16	3.08	0.09
K	21.00 ± 2.39	24.55 ± 3.55	24.27 ± 2.34	21.40 ± 2.21	0.41	0.74	0.29	0.59
Na	27.00 ± 2.02	28.00 ± 1.14	29.40 ± 1.49	25.40 ± 1.24	1.72	0.18	0.07	0.80
S	13.00 ± 1.22a	10.45 ± 1.40ab	8.07 ± 0.73b	8.53 ± 0.49b	3.94	0.01	7.27	0.01
Zn	0.84 ± 0.19	0.86 ± 0.17	0.74 ± 0.03	0.77 ± 0.09	0.25	0.86	0.07	0.79
CEC	3.66 ± 0.35	5.32 ± 0.79	5.53 ± 0.56	5.54 ± 0.67	1.08	0.37	3.11	0.09
pH	4.26 ± 0.15ab	4.21 ± 0.07ab	3.99 ± 0.07b	4.46 ± 0.07a	7.04	0.00	0.09	0.77
C	2.45 ± 0.55	2.47 ± 0.37	2.79 ± 0.33	1.79 ± 0.23	1.95	0.14	0.04	0.85
N	0.10 ± 0.02	0.07 ± 0.01	0.07 ± 0.01	0.06 ± 0.01	1.63	0.20	3.44	0.07
OM	4.23 ± 0.66	4.45 ± 0.62	4.91 ± 0.47	3.32 ± 0.44	2.01	0.13	0.00	0.99

[1] Units: S (ppm); cation exchange capacity (CEC) (cmol kg^{-1}); C, N, and OM (%); all others (mg kg^{-1}).

Table 2. Linear regression *p*-values and r^2 values for the prediction of soil chemical properties with fire frequency from 2004 to 2015 at the Tom Yawkey Wildlife Center, Georgetown, SC, USA.

Soil Chemical Property	Soil Depth 0–10 cm		Soil Depth1 0–20 cm	
	p-Value [1]	r^2	*p*-Value [1]	r^2
Al	0.13	0.05	0.40	0.02
B	0.69	0.00	0.95	0.00
Ca	0.01 (+)	0.16	0.31	0.02
Cu	0.41	0.02	0.79	0.00
Fe	0.17	0.04	0.25	0.03
Mg	0.65	0.00	0.07	0.07
Mn	0.00 (+)	0.23	0.06	0.08
P	0.96	0.00	0.46	0.01
K	0.74	0.00	0.04 (−)	0.09
Na	0.35	0.02	0.35	0.02
S	0.01 (−)	0.16	0.34	0.02
Zn	0.53	0.01	0.15	0.05
CEC	0.18	0.04	0.91	0.00
pH	0.13	0.05	0.01 (+)	0.16
C	0.18	0.04	0.73	0.00
N	0.06	0.08	0.82	0.00
OM	0.20	0.04	0.56	0.01

[1] Signs indicate an increase (+) or decrease (−) with increasing fire frequency.

3.2. Soil Depth 10–20 cm

Significant differences between the 2004 and 2015 treatment means at the 10–20 cm soil depth for 0, 4, 6, and 8 burns were determined for the following variables: Fe ($p < 0.01$), K ($p = 0.02$), Mn ($p = 0.04$), P ($p = 0.01$), soil pH ($p = 0.01$) (Table 3). Of these variables, Fe and K were greatest in the unburned compartment. Soil P was highest in compartments burned 6 times, but was only significantly different from the compartments burned 8 times. Manganese was highest in the compartments burned 8 times, but was only significantly different from compartments burned 6 times. Soil pH was greatest in compartments burned 8 times, but was only significantly different from compartments burned 4 and 6 times. Potassium ($p = 0.04$) and soil pH ($p = 0.01$) displayed significant relationships with fire frequency (Table 2). Potassium decreased with increasing fire frequency and soil pH increased with increasing fire frequency. The strength of these relationships was low, however, as both $r^2 \leq 0.16$. Using linear contrasts to compare the mean of all of the burned compartments from 1978 to 2015 to the mean of the unburned compartment from that time period for each of the variables, K ($p = 0.00$) and Fe ($p < 0.01$) were the only variables that indicated a significant reduction based upon fire inclusion from 1978 to 2015. The remaining comparisons yielded $p > 0.05$.

Table 3. Soil chemical property means (±standard error) at the 10–20 cm soil depth based upon fire frequency from 2004 to 2015 and linear contrast results for fire inclusion from 1978 to 2015 at the Tom Yawkey Wildlife Center, Georgetown, SC, USA. Means with different lowercase letters are statistically different at α = 0.05.

Soil Property (10–20 cm) [1]	Means ± Standard Error for Fire Treatments, 2004–2015						Burned vs. Unburned Contrast, 1978–2015	
	0 Burns n = 5	4 Burns n = 11	6 Burns n = 15	8 Burns n = 15	ANOVA Stat	ANOVA p-Value	Contrast Stat	Contrast p-Value
Al	1149 ± 159	1128 ± 169	975 ± 137	1003 ± 85	0.35	0.79	0.26	0.61
B	0.41 ± 0.02	0.36 ± 0.05	0.27 ± 0.04	0.39 ± 0.04	1.83	0.16	0.88	0.35
Ca	166 ± 47	172 ± 40	151 ± 26	221 ± 37	0.86	0.47	0.07	0.80
Cu	0.12 ± 0.02	0.17 ± 0.03	0.12 ± 0.01	0.14 ± 0.02	1.00	0.40	0.35	0.55
Fe	240 ± 35a	123 ± 17bc	100 ± 14c	159 ± 10b	9.80	<0.01	20.05	<0.01
Mg	22.80 ± 1.07	22.91 ± 1.89	21.33 ± 1.19	19.07 ± 1.61	1.26	0.30	0.43	0.52
Mn	0.84 ± 0.04ab	0.91 ± 0.11ab	0.80 ± 0.01b	1.36 ± 0.25a	3.12	0.04	0.43	0.53
P	7.60 ± 0.93ab	9.82 ± 1.23ab	11.93 ± 1.41a	7.07 ± 0.42b	4.32	0.01	1.18	0.28
K	16.40 ± 0.87a	11.09 ± 0.83b	10.93 ± 0.85b	11.13 ± 1.03b	3.85	0.02	11.49	0.00
Na	23.20 ± 1.30	22.82 ± 0.88	22.87 ± 1.09	21.67 ± 1.04	0.39	0.76	0.18	0.67
S	17.00 ± 1.76	15.91 ± 3.20	16.00 ± 2.85	13.20 ± 1.27	0.39	0.76	0.22	0.64
Zn	0.68 ± 0.26	0.78 ± 0.21	0.67 ± 0.15	0.44 ± 0.05	1.02	0.39	0.05	0.82
CEC	3.10 ± 0.70	3.48 ± 0.85	2.84 ± 0.39	3.26 ± 0.48	0.24	0.87	0.01	0.92
pH	4.56 ± 0.04ab	4.53 ± 0.09b	4.57 ± 0.05b	4.80 ± 0.05a	4.51	0.01	0.48	0.49
C	1.09 ± 0.09	1.20 ± 0.19	1.15 ± 0.18	1.05 ± 0.18	0.12	0.95	0.02	0.88
N	0.06 ± 0.00	0.05 ± 0.01	0.06 ± 0.01	0.06 ± 0.01	0.16	0.92	0.00	0.99
OM	1.65 ± 0.23	1.88 ± 0.25	1.58 ± 0.22	1.59 ± 0.26	0.32	0.81	0.01	0.93

[1] Units: S (ppm); CEC (cmol kg^{-1}); C, N, and OM (%); all others (mg kg^{-1}).

4. Discussion

4.1. Fire Frequency (2004–2015)

Increasing fire frequency from 2004 to 2015 was poorly correlated with mineral soil chemical property values in this study. At the 0–10 cm soil depth, both Ca and Mn were highest in the forest compartments burned 8 times from 2004 to 2015. The Ca values at this depth were double and significantly different from the compartment burned 0 times during those years. Potential increases in these values may be beneficial for tree growth and health as Ca is important for cell wall formation and nitrate (NO_3^-) uptake and Mn is an important component of enzymes utilized in oxidation–reduction processes [39].

Contrasting with the conclusion of Pellegrini et al. [27], significant reductions in C and N at both soil depths were not noted as a result of increasing fire frequency. It should be noted that the study at Yawkey is specific to prescribed fire, and more specifically, dormant season, low-intensity, low-severity surface fires in a longleaf pine-dominated forest with sandy surface soil horizons. In any study of fire frequency, intensity and severity are critical components [5]. Increased wildfire frequency, often typified by both high intensity and severity, would most likely have different short- and long-term impacts than areas undergoing an increased prescribed fire frequency [11]. Compounded in these effects would be the type of vegetation present, recent disturbance history of a given site, and the expected fire return interval for that community [4]. Our results from Yawkey are specifically representative of pine stands on sandy sites of the U.S. southeastern Coastal Plain and such conditions are representative of a substantial proportion of pine forests in the region. It is estimated that 2.8–3.2 million ha (7–8 million acres) are currently maintained with prescribed fire in this region [31] and additional acreage is predicted for the future as more individuals and groups focus on longleaf pine restoration [40]. However, our study does not address stands that might require a first-entry prescribed burn, a situation which requires the consideration of multiple factors prior to prescribed fire implementation, such as both duff mass and depth [41].

Our findings also allude to the inherent complexity of categorizing and characterizing fire's effects on soils in a broadcast fashion [11,21]. Soils and associated vegetation are inherently highly variable across the landscape [21]. Soil responses to fire have also been shown to vary with depth, especially when forest floor (Oi + Oe) and mineral soil distinctions are considered [11,28]. Therefore, a given nutrient or property may not be uniform across forest stands. Furthermore, fire interacts uniquely with the fuel components within a specific locality, even within a specific ignition [42–44]. Loudermilk et al. [44] postulated that the distinct parameters of a "fuel cell" in longleaf pine units, like those at Yawkey, may be unique from one 0.25 m^2 area to the next. This inherent complexity of both soil properties and fire events make a characterization of fire effects across differing soils challenging, if not impossible, even when describing increasing fire frequency. As such, each given fire regime in a given ecological complex merits investigation of unique effects rendered to soil properties and processes.

4.2. Fire Inclusion (1978–2015)

The linear contrasts indicated that long-term prescribed fire use, regardless of short-term frequency, enacted minimal changes to forest soil properties. These results align with other studies in the southeastern region of the USA [12,28,30,45]. These studies found minimal to non-significant soil N impacts with long-term prescribed fire use. Binkley et al. [28] and Boyer and Miller [29] noted a lack of significant change in soil P, but McKee [12] investigated long-term fire use in the Coastal Plain and found elevated P and Ca levels with fire inclusion. Carter and Foster [21] postulated that these discrepancies might be related to differences in fire severity, the length of time between sample collection and burning, or different measures of P availability.

Outside of the southeastern Coastal Plain, Neill et al. [46] found that burning in a Cape Cod oak–pine forest every 1–4 years in spring or summer had little effect on soil chemistry, including nonsignificant effects on mineral soil percent C, N, Ca, Mg, and K. In this study, the authors also compared burning season effects: spring (March/April) versus summer (July/August) burns. They determined that annual summer burns were most effective for OM thickness reduction, a variable of interest for the establishment of grasses and oaks in their region. Meier [47] found that long-term, periodic and annual burning in the Missouri Ozarks led to reductions in mineral soil C and increases in mineral soil N to the 7 cm soil depth. These burns were conducted to simulate uncontrolled fires, however, as opposed to standard prescribed fires characteristic of those conducted by managers and practitioners in the region. Recently, in an Illinois hardwood forest subjected to 30 years of annual prescribed fire, Taylor and Midgley [48] reported that: (1) soil N availability increased, (2) soil P was not affected, and (3) soil total C increased, although soil C availability was not altered. In their synthesis of these results, the authors suggested that the lack of C and N reduction as a result of this practice may limit annual burning as an effective response to concerns regarding ecosystem restoration and renewed oak regeneration. Similar results in Appalachian hardwood forests have been reported regarding the implications of singular implementations of prescribed fire and other fuel reduction treatments in Ohio and North Carolina [49].

Additionally, some of the long-term results match well with short-term study results. Coates et al. [50] found that first-entry fuel reduction treatments in the southern Appalachian Mountains, including prescribed fire, shrub felling, and a combination of shrub felling and prescribed fire, induced little change to forest soil properties and processes up to 4 years post-treatment. A combination of both mechanical shrub felling and prescribed fire did produce reductions in soil Fe at the 0–10 cm soil depth, similar to the results noted at Yawkey with prescribed fire only. Iron is required as part of plant redox systems and is needed for some proteins [51]. Mehlich 3-extractable Fe has been poorly correlated with plant-available Fe [52], however, and that impairs our ability to interpret the biological significance of this finding. Knoepp et al. [53] found that fell-and-burn site preparation in the southern Appalachian Mountains of western North Carolina did not affect total soil C or N or total soil nutrients up to 5 years post-treatment. Rau et al. [54] noted in a study of soils in the central Great Basin that prescribed fire induced increases in surface soil Ca (0–8 cm depth). The increases in soil pH noted at Yawkey for the 0–10 cm soil depth have most often been noted as a short-term response across multiple locations [55–57]. The additional linear contrasts for S at the 0–10 cm soil depth and K and the 10–20 cm soil depth should be taken into consideration based upon the inherent values of the sandy, Coastal Plain soils being studied and the potential needs of plants in this ecosystem.

It is important to emphasize that sample sizes for our study were limited, particularly in the long-term unburned compartment. An increase in samples size could enhance confidence in inferences gleaned from this study. Additionally, we had access to only one unburned compartment. Additional studies at other long-term, unburned locations in this region would undoubtedly improve interpretations and expand the scope of inferences. However, these data do support the findings of Coates et al. [58], which concluded that the frequent, prescribed, low-intensity, low-severity, surface fires at Yawkey did not significantly alter the chemical composition of forest floor materials. The chemical functional groups, including selected polycyclic aromatic hydrocarbons (PAHs), of both burned and unburned litter and duff, showed little to no alteration as a result of prescribed fire. These compounds are known black carbon (or pyrogenic carbon, PyC) constituents, exhibiting both mutagenic and potentially carcinogenic properties when ingested by humans, as might occur when these compounds impact surface waters treated for human consumption [59]. For forest soils of these sites, it appears that prescribed fire implementation has successfully enhanced wildlife habitat, reduced potentially hazardous fuel loading with low fire intensity and severity [60], and maintained long-term soil chemistry.

5. Conclusions

The Tom Yawkey Wildlife Center has used frequent, low-intensity, low-severity, prescribed, surface fires to reduce hazardous fuels and improve wildlife habitat for an endangered wildlife species since (at least) 1978. Their management objectives, implemented through prescribed fire, have resulted in no substantial indications of major soil effects. Specifically, increasing fire frequency from 2004 to 2015 was not significantly correlated with negative alterations in forest mineral soil chemical properties at the 0–10 and 10–20 cm soil depths. Both Ca and Mn were highest at both depths in compartments that were burned 8 times from 2004 to 2015; Ca at the 0–10 cm soil depth was double the value of the unburned compartment. The use of prescribed fire from 1978 to 2015, regardless of short-term frequency from 2004 to 2015, did produce significant reductions in Fe at both depths, S at the 0–10 cm soil depth, and K at the 10–20 cm soil depth. Implications for these reductions should be considered in light of additional soil parameters and metrics. Contrary to several recent studies, alterations in C and N were not noted as a result of long-term fire inclusion or increasing fire frequency at Yawkey. Continued research is needed in this region to understand how frequent prescribed fire affects forest soil properties and processes while accomplishing broader land management objectives, especially as prescribed fire acreage throughout this region continues to grow on an annual basis and concerns continue to mount regarding wildfire hazard under changing climatic conditions. Overall, prescribed fires have been used across the southeastern Coastal Plain for thousands of years and pine ecosystems are maintained by such disturbances. It appears that judicious application of prescribed fire within the region on similar sites with sandy surface horizons can result in numerous beneficial effects with minimal concern for long-term soil chemistry.

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