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# Intra-Annual Variation in Soil C, N and Nutrients Pools after Prescribed Fire in a Mississippi Longleaf Pine (*Pinus palustris* Mill.) Plantation

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Received: 19 December 2019; Accepted: 4 February 2020; Published: 6 February 2020

**Abstract:** Prescribed fire is an essential tool that is widely used for longleaf pine (*Pinus palustris* Mill.) stand management; periodic burning serves to reduce competition from woody shrubs and fire-intolerant trees and enhance herbaceous diversity. Low-intensity, prescribed burning is thought to have minimal long-term impact on soil chemistry in southern pine forests, although few studies report the intra-annual variation in soil chemistry after burning. We monitored changes in C, N, oxidation resistant C ($C_R$), pH and elemental nutrients in the forest floor and soil (0–5, 5–10 cm depths) before and after burning (1, 3, 6, 12 months) in a mature longleaf pine plantation at the Harrison Experimental Forest, near Saucier, Mississippi. Prescribed fire consumed much of the forest floor (11.3 Mg ha$^{-1}$; −69%), increased soil pH and caused a pulse of C, N and elemental nutrients to flow to the near surface soils. In the initial one to three months post-burn coinciding with the start of the growing season, retention of nutrients by soil peaked. Most of the N (93%), Ca (88%), K (96%) and Mg (101%), roughly half of the P (48%) and Mn (52%) and 25% of the C lost from the forest floor were detected in the soil and apparently not lost to volatilization. By month 12, soil C and N pools were not different at depths of 0–5 cm but declined significantly below pre-burn levels at depths of 5–10 cm, C −36% ($p < 0.0001$), N −26% ($p = 0.003$), contrary to other examples in southern pine ecosystems. In the upper 5 cm of soil, only Cu (−49%) remained significantly lower than pre-burn contents by month 12, at depths of 5–10 cm, Cu (−76%), Fe (−22%), K (−51%), Mg (−57%), Mn (−82%) and P (−52%) remain lower at month 12 than pre-burn contents. Burning did not increase soil $C_R$ content, conversely significant declines in $C_R$ occurred. It appears that recovery of soil C and N pools post-burn will require more time on this site than other southern pine forests.

**Keywords:** forest soils; prescribed fire; carbon; nitrogen; phosphorus; potassium; calcium; priming; Harrison Experimental Forest; longleaf pine

## 1. Introduction

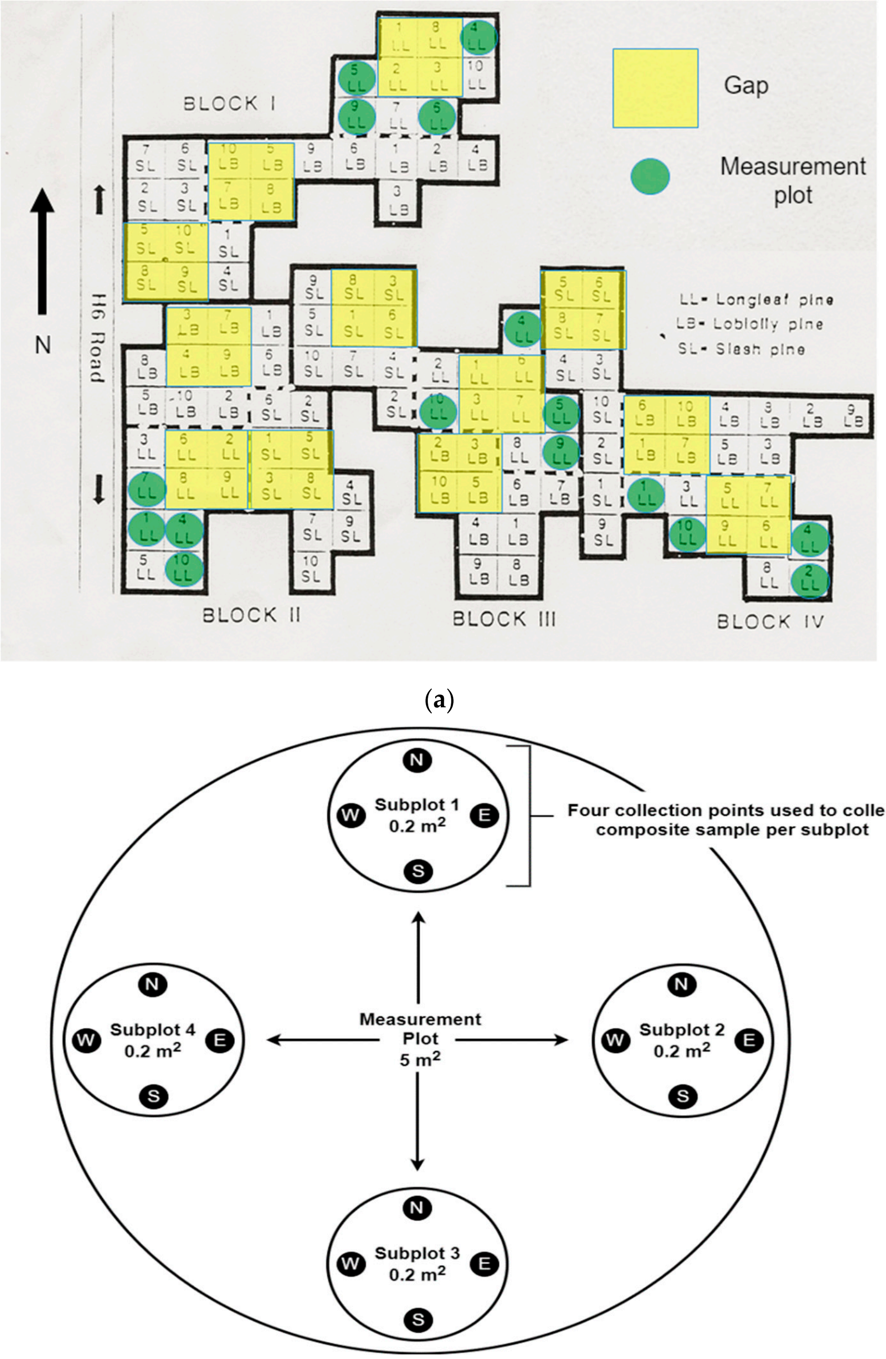
Prescribed fire is an essential tool that is widely used for longleaf pine (*Pinus palustris* Mill.) stand management and restoration of associated fire-adapted ecosystems [1]. Periodic fire serves to reduce competition from woody shrubs and deciduous trees, improve forage quality and enhance herbaceous diversity [2]. Longleaf pine seedlings have an extended "grass" stage [3] where they are more resistant to fire damage than other southern pine seedlings especially loblolly pine (*Pinus taeda* L.), which is a prolific volunteer in many young pine plantations [4]. Older, uneven-aged stands are characterized by lower stand densities, endemic fire-adapted plant species and threatened animal species such as the gopher tortoise (*Gopherus polyphemus* Daudin) and the red-cockaded woodpecker (*Leuconotopicus borealis* Vieillot) [2].

Low-intensity, dormant season fires consume a portion of the biomass held in fire-sensitive trees and shrubs, herbaceous plants, down woody debris, leaf litter and the forest floor. Prescribed fires release carbon (C) and mobilize elemental nutrients immediately resulting in losses to volatilization or deposited on the soil surface [5]. Subsequent weathering and precipitation facilitate the movement of nutrients into the soil where plant uptake and soil stabilization may take place or conversely water may facilitate the loss of nutrients via leaching. Prior studies in southern pine stands report results from multiple burn cycles [6,7] or periods of one to three years after burning [8]; in these studies there were no residual differences in soil C or nitrogen (N) content after one year. Dormant season burns are well timed for plants to uptake nutrients at the start of the growing season when nutrient demand is high and soil moisture is typically not limiting. More intense fires and growing-season fires consume more biomass than low intensity fires, have longer lasting effects on soil chemistry and can leap into crowns or scorch current year leaves and shoots. Using a meta-approach, Nave, et al. [9] concluded that prescribed burns did not affect C and N storage, although significant reductions may coincide with wildfires.

The general consensus that low intensity, prescribed fires have little long-term impact on soil chemistry, comes with a caveat; there are short-lived increases in soil nutrients, available N and pH [5,10]. Depending on the intensity of the fire, loss of elemental nutrients via volatilization and transfer to the atmosphere are known to occur, particularly N, P, K, Mg, Mn and B [11,12]. Currently there are few comprehensive intra-annual reports of changes in soil chemistry in longleaf pine plantations associated with prescribed fire. Using frequent sampling at a lower coastal plain site in Mississippi, our study attempts to quantify ephemeral fluctuations of soil chemistry after prescribed fire to better understand the transfer of nutrients from the forest floor to near-surface soils. In addition to monitoring bulk soil C over an intra-annual time series, we assessed the oxidation resistant C fraction representing a combination of charcoal and mineral associated C [13–15] to better evaluate changes in stability related to burning.

## 2. Materials and Methods

The study was conducted in a 54-year-old longleaf pine plantation on the Harrison Experimental Forest near Saucier, MS (30.65 N, 89.04 W, elevation 50 m). The soils are variable and are classified as the Poarch and Saucier series (coarse loamy, siliceous, semiactive, thermic Plinthic Paleudults) and the Saucier–Susquehanna complex. In the study plantation, the soils are well drained with slopes ranging from 1%–4%. The plantation is characterized as being phosphorus (P) deficient (16 kg P $ha^{-1}$ upper 30 cm of soil) with relatively low soil C and N contents [16]. The site has no known history of agriculture, consistent with its low fertility. The original longleaf pine stand was cut in the early 1900s and naturally regenerated. In 1960, the stand was clearcut and the present day plantation was established and used to study the effects of one-time application of fertilizer (among other silvicultural treatments) on growth and wood quality [17]. Later studies examined the relative wind firmness of longleaf pine compared to loblolly and slash pine (*Pinus elliottii* Engelm.) [18], and the long-term effects of the initial treatments on soil C and N pools [16]. The plantation was burned in 2010, followed by a partial harvest in 2011, where 48 of the original 120 (−0.2 ha) plots were harvested to establish gaps and the remainder thinned leaving a residual basal area ranging from 8.3 to 26.8 $m^{-2}$ (Figure 1a). Using the blocking design described by Schmidtling [17], four thinned longleaf pine plots were randomly selected in each of four blocks (total of 16 plots) for intra-annual sampling before and after prescribed fire on 28 February 2014. The soils are diverse on the Saucier–Susquehanna complex and the blocking design constrains differences in soil texture and slope. The harvested gaps were not examined in the present study as they possessed minimal forest-floor development from site preparation following the 2011 harvest. Rainfall and air temperature were monitored at the site with a Campbell Scientific weather station (Campbell Scientific, Inc., Logan, Utah) and reported as monthly precipitation and mean monthly air temperature for the 12 months following the prescribed burn (Figure 2).



(**a**)

(**b**)

**Figure 1.** Map of study site at the Harrison Experimental Forest near Saucier, Mississippi, where green circles denote the location of 16 measurement plots and yellow squares identify 12 gaps that were harvested (**a**). Within each 5 m$^2$ measurement plot, four 0.2 m$^2$ subplots were located 1 m from center (**b**).

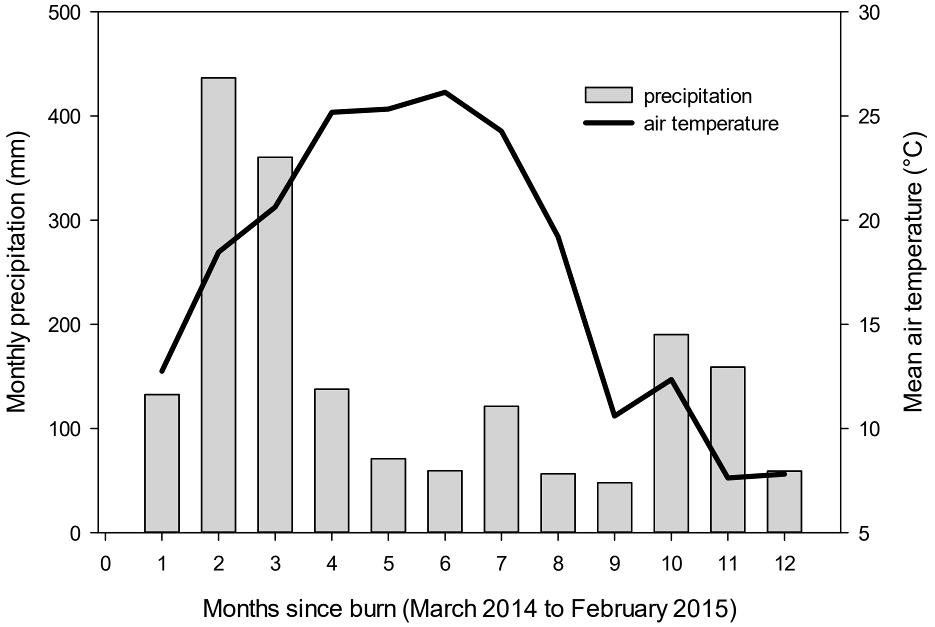


**Figure 2.** Monthly precipitation and monthly mean air temperature at the Harrison Experimental Forest near Saucier, Mississippi, for the 12 months following prescribed burning on 28 February 2014.

A metal marker was placed at the center of each pre-existing 0.2 ha plot where a circular measurement plot (5 $m^2$) was established. Each measurement plot had four subplots (0.2 $m^2$) established 1 m away from plot center at cardinal directions (Figure 1b). The subplots were sampled for forest floor and soil nutrients at 0–5 cm depth and 5–10 cm depth in January 2014, and again 1, 3, 6 and 12 months after prescribed fire for a total of five repeated measures. The forest floor was a combined sample of leaf litter, woody debris and organic matter above the mineral soil layer. At each subplot, samples were collected 25 cm away from subplot center at 4 cardinal points with a 2.7 cm-diameter soil core and combined to create a composite sample, holes were re-filled with forest soil and a pin flag was placed in the sample hole as to avoid re-sampling on disturbed soil. The intention was to collect a thorough, representative sample from a relatively small area to be able to detect changes over time. Soil bulk density cores and texture samples were collected (0–10 cm depth) in the main plots prior to the burn in January 2014. Soil bulk density was reassessed at the final collection period (month 12 post-burn) with 5 cm diameter collection cylinders at 0–5 cm and 5–10 cm depths from each subplot.

Forest floor mass loss, soil bulk density, soil texture [19] as well as C and N (dry combustion, Carlo Erba NA 1500 Series II C/N/S Analyzer, Fison Instruments, Danvers, MA, USA) were analyzed at the USDA Forest Service, Forestry Sciences Laboratory in Research Triangle Park, North Carolina. Bulk forest floor and soil available macro and micronutrients (Ca, Cu, Fe, K, Mg, Mn, Na, P) and pH were analyzed at a commercial laboratory (Spectrum Analytic, Washington Court House, OH, USA). Forest floor samples were dry ashed with a muffle furnace, digested with 20% HCl and analyzed with a Thermo Jarrell Ash 61 E inductively coupled plasma spectrometer (ICP). Soil samples were extracted with Mehlich III extracting solution prior to analysis with the ICP [20]. In addition to bulk soil C and N analysis, the soils were chemically fractionated with 20% $H_2O_2$ and 0.3 M $HNO_3$ to isolate oxidation resistant carbon ($C_R$) using a protocol described by Butnor, et al. [21] and analyzed via dry combustion (Carlo Erba NA 1500 Series II C/N/S Analyzer, Fison Instruments, Danvers, MA, USA). The protocol was based on the work of Kurth, MacKenzie and DeLuca [15] and Ball, MacKenzie, DeLuca and Holben [14] who used the approach to isolate charcoal in organic soils. Similar $H_2O_2$ fractionation protocols have been also used to isolate mineral protected C in both mineral and organic soils [13]. It should be considered a general assay for oxidation-resistant C, but not pyrogenic C per se [21].

The original intensive culture experiment circa 1961 was a randomized complete block design wherein the range of silvicultural treatments (control, disking for weed control, disking plus one time fertilizer application) were randomized into four blocks [17]. In the present study, we forgo examination of past treatments, but retain the 4 blocks to constrain variability related to soil heterogeneity [16] creating a complete block design (Figure 1). Regardless of whether there are pre-existing differences in soil chemistry from microsite, stand density, soil moisture, soil type or prior treatments from 50 years ago [16], the repeated measures experimental design serves to quantify the changes in chemistry in the months following the prescribed fire. Mixed model (Proc Mixed) repeated measures analysis (RMA) was used to evaluate changes in soil C and nutrient pools over time [22] utilizing the complete block design described above. It was necessary to use the power (type = sp (pow)) covariance structure to account for unequally spaced observations. Least square means with the Bonferroni correction were used to evaluate differences in nutrient concentration between specific observation periods. Change in soil bulk density before and one year after fire was analyzed by comparing the 0–10 cm values (pre-fire) to the average of 0–5 and 5–10 cm (post-fire) with RMA. It was necessary to use the post-fire bulk density values for pool determination as nutrient analysis was performed at 5 cm-depth intervals.

## 3. Results

### 3.1. Fire Effects on Soil Nutrients and pH

One month after prescribed fire the mass of forest floor was reduced by 11.36 Mg ha$^{-1}$, representing a reduction of −69% (Table 1). Similar significant reductions in the C, $C_R$ and N pools were noted (Table 1), while there were no significant block effects. Soil bulk density (0–10 cm) significantly declined 12% from pre-burn (1.38 g cm$^{-3}$) to one year after (1.22 g cm$^{-3}$) the prescribed fire (F = 14.0, P = 0.0028). Immediately following the fire, increases in C and N concentration were noted in forest floor and soil 0–5 cm (not always significant), but not soil 5–10 cm (Figure 3a,b). In soil 0−5 cm, after peak concentrations of C and N at month 3, concentrations were significantly lower than peak by month 12 (Figure 3a,b). Without accounting for the temporary pulse in concentration, pre- and post-burn soil C and N concentrations were not significantly different at depths of 0–5 cm by month 12: C −20% ($p$ = 0.28), N −13% ($p$ = 0.14). Soil 5–10 cm experienced significant declines in C and N concentration from pre-burn to post-burn: C −36% ($p < 0.0001$), N −26% ($p$ = 0.003) (Figure 3a,b). Using forest floor mass and soil bulk density, C and N concentrations were scaled to the stand level (Mg ha$^{-1}$) and showed trends similar to that of the concentrations (Figure 3c,d). Soils at both depths experienced statistically significant declines in C:N ratio through month 6 that were no longer different than pre-burn conditions by month 12 (Figure 3e). Soil $C_R$ concentration (a subset of total soil C) declined significantly over the 12-month observation period (Figure 4a) and surprisingly its proportion of the total C pool declined as well (Figure 4b).

**Table 1.** Change in forest floor mass, C, N and nutrient pools one-month post-burn.

| Pool | Pre-Burn (kg ha$^{-1}$) | Post-Burn (kg ha$^{-1}$) | Change (%) |
|---|---|---|---|
| Total mass | 16,413 ± 1481 | 5051 ± 845 | −69 |
| C | 6402 ± 688 | 2426.9 ± 427 | −62 |
| N | 91.1 ± 10.8 | 33.9 ± 6.0 | −63 |
| $C_R$ | 210.0 ± 20.0 | 100 ± 20.0 | −48 |
| Ca | 49.9 ± 5.4 | 5.8 ± 0.9 | −95 |
| Cu | 0.18 ± 0.09 | 0.01 ± 0.0002 | −94 |
| Fe | 35.1 ± 3.9 | 0.2 ± 0.03 | −99 |
| K | 7.5 ± 1.2 | 0.75 ± 0.14 | −90 |
| Mg | 6.6 ± 0.7 | 1.5 ± 0.3 | −77 |
| Mn | 4.5 ± 0.7 | 0.3 ± 0.05 | −93 |
| Na | 0.81 ± 0.08 | 0.14 ± 0.03 | −83 |
| P | 3.2 ± 0.5 | 0.14 ± 0.03 | −95 |

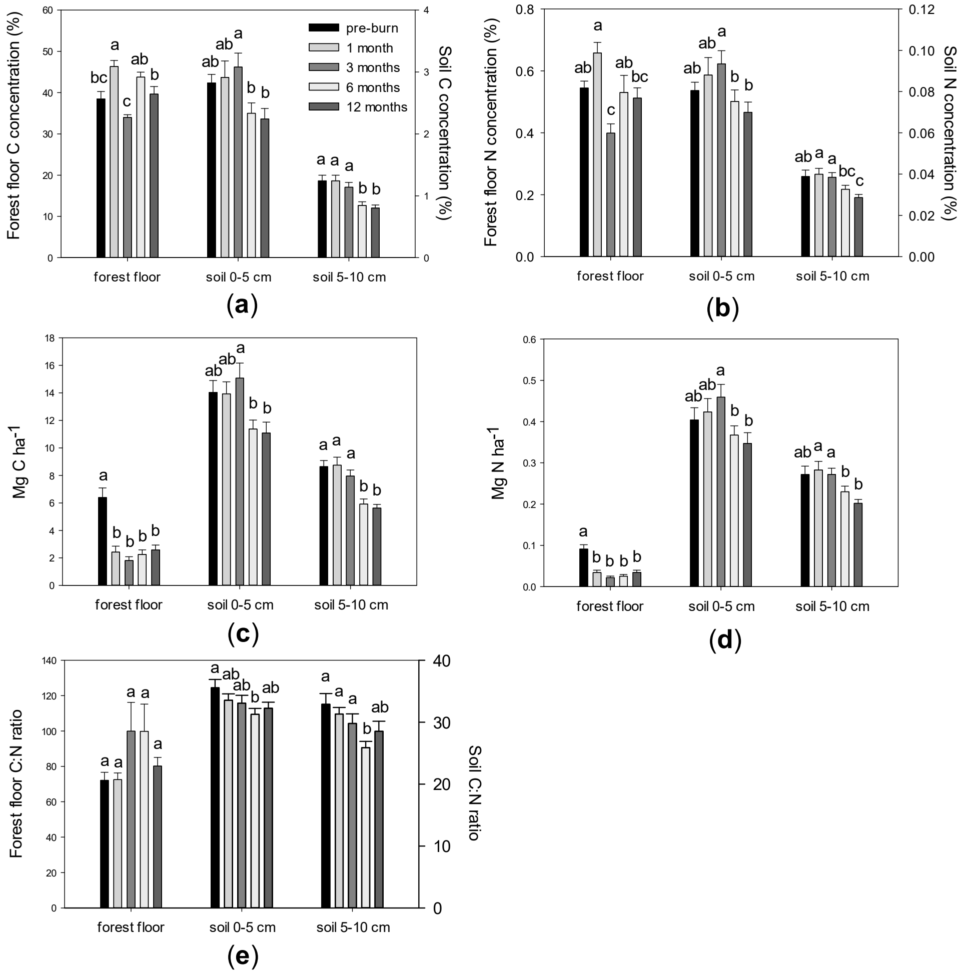


**Figure 3.** C and N concentrations (**a**,**b**), C and N pools (**c**,**d**) and C:N ratios (**e**) of forest floor and soil collected pre-burn and 1, 3, 6, and 12 months after the fire. Within each group, means with the same letter do not differ at $p < 0.05$ and error bars represent the standard error of the mean. Note that **a**, **b** and **e** have separate x axes scaled for forest floor and soil, respectively.

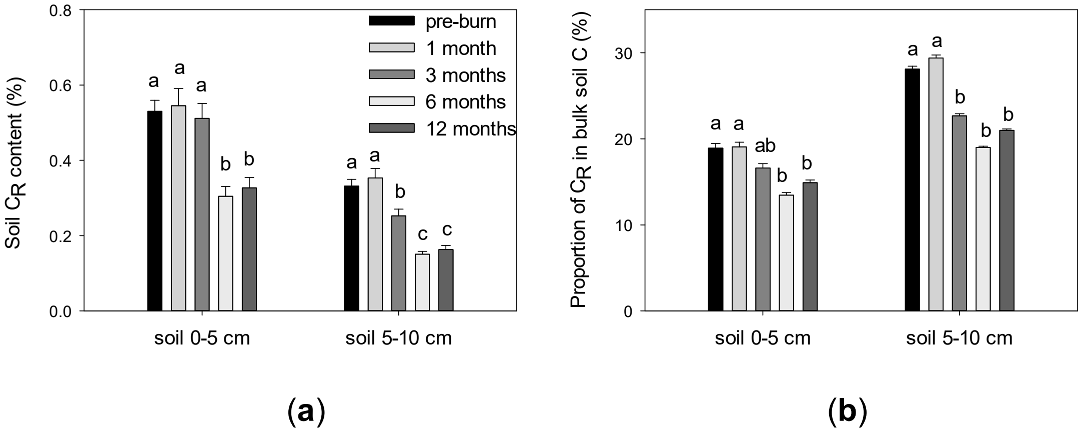


**Figure 4.** Oxidation resistant soil C ($C_R$) content of soils from depths of 0–5 and 5–10 cm (**a**) and the proportion of $C_R$ in bulk soil C (**b**). Within each group, means with the same letter do not differ at $p < 0.05$ and error bars represent the standard error of the mean.

Similar to C and N, reductions in forest floor macro and micronutrients (Ca, Cu, Fe, K, Mg, Mn, Na, P) ranged from −77 to −99% after prescribed fire (Table 1). Figure 5 shows the mean nutrient contents across the five observation periods, with most being lower 12 months after the fire. Soil Ca, K, Mg, and P increased temporarily following prescribed fire, presumably from release from the forest floor layer. Soil pH increased significantly from pre-burn condition to month 6 (Figure 6), due the liming effect of biomass ash and Ca release from the forest floor layer. The relative change in soil nutrients and C and N across the 12 month period is visualized in Figure 7a,b. In the upper 5 cm of soil, only Cu (−49%) remained significantly lower than pre-burn contents by month 12, at depths of 5–10 cm, Cu (−76%), Fe (−22%), K (−51%), Mg (−57%), Mn (−82%) and P (−52%) remain lower at month 12 than pre-burn contents (Figure 5).

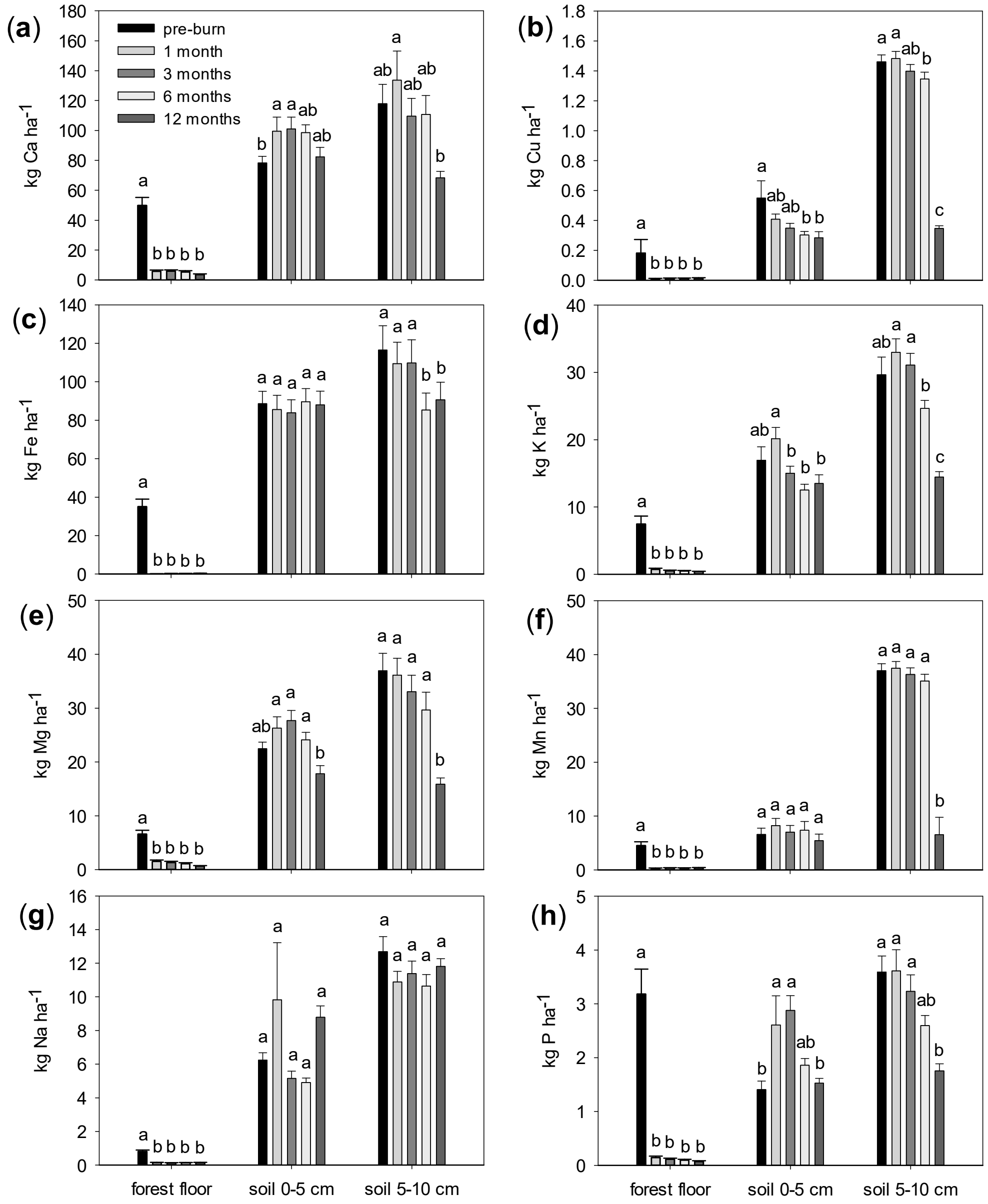


**Figure 5.** Soil nutrient content of Ca, Cu, Fe, K, Mg, Mn, Na, and P (**a**–**h**) from samples collected pre-burn, followed by collections 1, 3, 6, and 12 months after the fire. Within each group, means with the same letter do not differ at $p < 0.05$ and error bars represent the standard error of the mean.

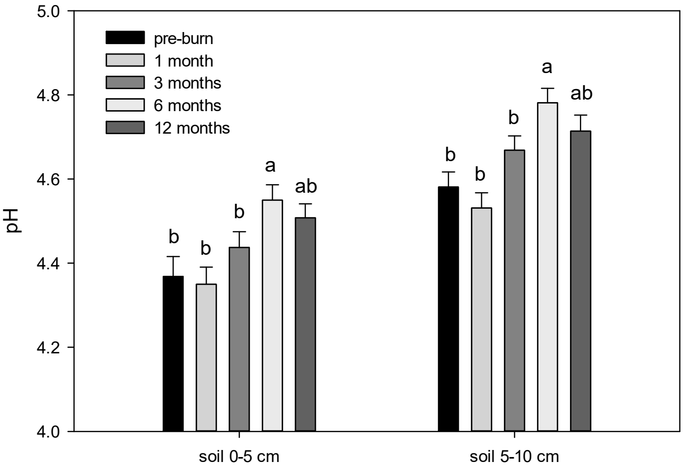


**Figure 6.** Soil pH from samples collected pre-burn, followed by collections at 1, 3, 6, and 12 months after the fire. Within each group, means with the same letter do not differ at $p < 0.05$ and error bars represent the standard error of the mean.

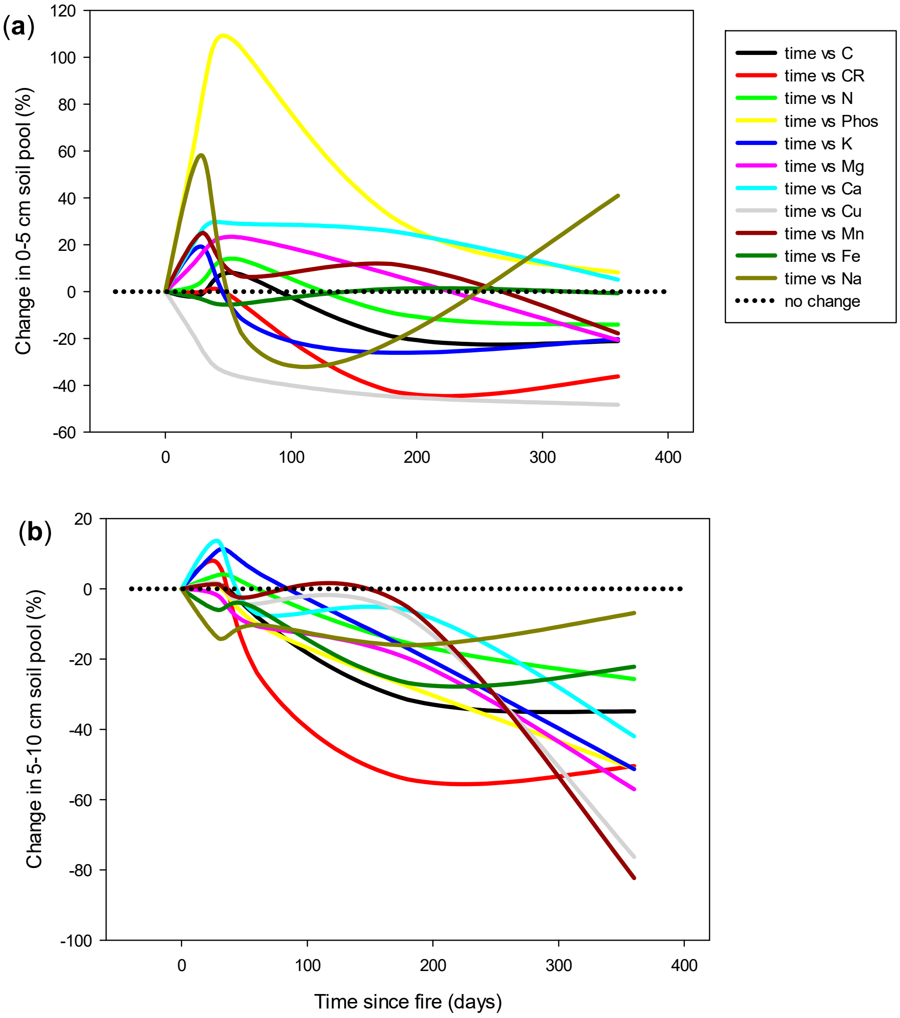


**Figure 7.** Percent change in soil C, $C_R$, N, macro and micronutrients from samples collected pre-burn and 1, 3, 6, and 12 months after the fire at depths of 0–5 (**a**) and 5–10 cm (**b**).

### 3.2. Retention of C, N and Nutrients Released by Combustion

We calculated the mass release of C, N and elemental nutrients from the forest floor layer and their peak retention in the 0–5 cm and 5–10 cm soils. One month post-fire, Ca, Cu, K, and Mn peaked, while C, N, Mg and P peaked at month 3 (Table 2). There could be very ephemeral responses that fall outside of the four post-fire observations at months 1, 3, 6 and 12, but there was a high rate of transfer of key nutrients from forest floor to soil. When the soil depths are combined (0–10 cm) retention of key nutrients were noted at 1 month: Ca, 88% and K, 96% and at 3 months: N, 93%; Mg, 101% and P, 48% (Table 2). The retention of these nutrients is temporary (Figures 3 and 5) and their fate beyond the 0–10 cm depth is unknown. These results also parameterize the amount of C (−25%, 1036 Mg C $ha^{-1}$) that was removed from forest floor by combustion, but not lost immediately to volatilization per se. Note that combustion of 69% of the forest floor layer did not increase soil $C_R$ beyond its initial concentration prior to burning (Figure 4).

**Table 2.** Peak retention of C, N and nutrients released via combustion from forest floor layer (Table 1) by soil at depths of 0–5 and 5–10 cm during 12 months of monitoring. The timing of peak retention is indicated by the variable Month.

| Pool | Month | Soil 0–5 cm (kg $ha^{-1}$) | % | Soil 5–10 cm (kg $ha^{-1}$) | % | Combined (kg $ha^{-1}$) | % |
|---|---|---|---|---|---|---|---|
| C | 3 | 1035.8 | 25 | – | – | 1035.8 | 25 |
| N | 3 | 55.1 | 93 | – | – | 55.1 | 93 |
| $C_R$ | | – | – | – | – | – | – |
| Ca | 1 | 21.2 | 48 | 17.7 | 40 | 38.9 | 88 |
| Cu | 1 | – | – | 0.02 | 12 | 0.02 | 12 |
| Fe | | n.s. | – | – | – | – | – |
| K | 1 | 3.2 | 47 | 3.3 | 49 | 6.5 | 96 |
| Mg | 3 | 5.2 | 101 | – | – | 5.2 | 101 |
| Mn | 1 | 1.7 | 40 | 0.5 | 12 | 2.2 | 52 |
| Na | | n.s | – | n.s | – | n.s | – |
| P | 3 | 1.47 | 48 | - | – | 1.47 | 48 |

## 4. Discussion

Burning is a normative practice in longleaf pine stand management and fire return intervals of 3–5 years are typical. Fire exclusion is not part of operational management as it encourages fire-intolerant competition and reduces understory diversity. Consequently, the long-term experiment that our study is embedded in does not have a fire exclusion component. Our experimental design is reliant on repeated measures [8,23,24] and does not have unburnt controls, therefore we cannot categorically distinguish the potential contribution of natural annual variation during our time series, unlike studies with unburnt controls [6,7]. Our findings that both soil C and N pools are significantly lower at the 5–10 cm depths one year after burning is contrary to other reports in southern pine forests located in: northern Florida (1 year post-fire) [8], the Crossett Experimental Forest, Arkansas (16 months post-fire) [7], and the Francis Marion National Forest, South Carolina (1 year post-fire) [6]. Similarly, declines in elemental nutrients at depths of 5–10 cm in our experiment were contrary to increases in Ca, K and Mg (5–10 cm) in northern Florida [8], and no change in Ca, K, Mg, P (0–10 cm) in the Francis Marion National Forest, South Carolina [6] one year postburn.

In the short-term, a pulse of C and N from burned biomass moved through the upper 10 cm of soil peaking 3 months post-burning before declining precipitously. The late-February fire was well timed for nutrient uptake by plants in the spring in southern Mississippi, however the significant decline in C and N at depths of 5–10 cm dropped below the pre-burn condition, suggesting a microbial priming effect or a change in soil physical properties that may have favored decomposition [23,25,26]. The elevation in pH post-fire may have also created more favorable conditions for microbial activity in these acidic soils [25,27]. Priming effects not only bulk soil organic C, but have also been shown to accelerate mineralization of refractory C [28]. Soils at the Harrison Experimental Forest in the present study contained approximately half of the C and N in the upper 10 cm of soil compared to soils at the Francis Marion National Forest while maintaining similar C:N ratios [6]. The difference in quantity may buffer comparatively C rich soils from ephemeral priming effects. Alteration of the soil surface by fire, e.g., removal of forest floor, residual charred material and an increase in surface temperatures can lead to enhanced $CO_2$ efflux and depletion of soil C stocks [23]. The lack of an unburnt control in our experiment limits our ability to definitively attribute declines C, N, and elemental nutrients at depths of 5–10 cm to microbial priming and the alteration of the soil surface by fire. Interannual variation in climate could affect contents of soil C, N and elemental nutrients, though the magnitude of the observed declines in C, N, Cu, Fe, K, Mg, Mn and P are larger than expected without disturbance. Without comparing multiple years, it is not possible to determine the influence of seasonal variation in precipitation and temperature versus the time since burn. Precipitation at the site was high in April and May 2014 at two- and three months post burn, the combined precipitation was 797 mm representing 43% of the annual rainfall during the 12 months post-burn (Figure 2). The pulse of rain could have affected to movement of nutrients beyond the depths studied, the degree to which this affected the results is not known. A more radical hypothesis that fires temporarily depress plant uptake of N for and thereby enhance soil nutrient pools from reduced demand was proposed by Ficken and Wright [29], in their study of N mineralization rates in longleaf pine stands in eastern North Carolina. A period of depressed plant demand followed by a resumption or accelerated demand could help explain our intra-annual observation of peak nutrient pools after burning followed by depression below pre-burn conditions. In hindsight, collection of foliar samples for C and N would have provided some evidence to test the demand reduction hypothesis. Lavoie, Starr, Mack, Martin and Gholz [8] detected a significant increase in understory foliar N four months post-burn in a *P. palustris*, *P. elliottii* forest, however, after one year, N returned to pre-burn conditions. Soil C and N were only measured at two and 320 days post-burn preventing direct comparisons of intra-annual fluctuations [8].

Soil bulk density was assessed using the entire 0–10 cm depth interval prior to burning and was measured depths of 0–5 cm and 5–10 cm one year after burning. A decline in bulk density (12%) was observed when the pre-burn condition was compared to the average of the 0–5 and 5–10 cm depths one year later. There were no intra-annual assessments of bulk density to indicate the timing or variance between sample dates related to this change. As soil nutrient concentrations were collected at depths of 0–5 and 5–10 cm it was necessary to scale them to mass/area using soil bulk density one-year post-burn. It is unknown whether the change soil bulk density post-burn was abrupt or gradual and this is a limitation of our study.

Soil $C_R$ at depths of 0–5 and 5–10 cm remained relatively stable and was not different than initial concentration until three months post-burn. At six months, both the concentration of $C_R$ and its relative proportion in bulk soil C dropped significantly, despite being a composite fraction of chemically stable charcoal and mineral-associated C [13–15,21]. This suggests that charcoal is not moving into the soil, instead it is remaining on the surface or is floating away during precipitation events given it is in the lightest fraction. In a range-wide study of longleaf pine soils, mean residence time of soil C increased linearly with proportion of $C_R$, mainly due the longevity of mineral associated C [21]. This implies that the pulse of labile C and N moving through the soil profile may be priming the decomposition of soil $C_R$ that predated the burn. Using glucose additions, Hamer, Marschner, Brodowski and Amelung [28] demonstrated that pyrogenic C derived from wood (oak) experienced a priming effect of 189% greater mineralization after 60 days relative to controls. Guenet, et al. [30], found that stable soil organic C is just as vulnerable to mineralization as labile C during priming events. Although mineral-associated soil C is considered to be a very stable C pool with low turnover rates [13,31], significant priming effects on mineral-protected soil C from fresh litter additions [32] and root exudates [33] have been reported in forest systems.

The prescribed fire reduced forest floor biomass by 11.3 Mg $ha^{-1}$, similar to reports by Bell and Binkley [34] for 2-year (11.3 Mg $ha^{-1}$) and 4-year (7.8 Mg $ha^{-1}$) fire return intervals. Although there is transfer of nutrients from forest floor to soil associated with burning, there exists a dichotomy in the prescribed fire literature, one concept is that little or no forest floor N is lost in low severity prescribed fires, e.g., Richter, et al. [35], Schoch and Binkley [36] and another, when fire transitions to become "severe" significant loss via volatilization occurs e.g., Raison, Khanna and Woods [11,12], Bell and Binkley [34], DeBano [37], DeBell and Ralston [38]. The effects of fire intensity on the fate of forest floor N become more difficult to disentangle when post-burn soil sampling intervals vary and are commonly a few days post-burn, followed by measures years later. The quantity of elemental nutrients lost to volatilization are related to temperature-specific elemental sensitivities [37]. Nitrogen is very sensitive to volatilization at temperatures as low as 200 to 375 °C [39], P and K are less sensitive than N, while Ca and Mg, are largely insensitive to volatilization in biomass fires [12].

In a study of low-intensity prescribed fire in eucalypt forests, percent losses due to volatilization of the following elements were reported from the litter and understory: N, 54–75%; P, 37–50%; K, 43–66%; Ca 31–34%; Mg, 25–49%; Mn 25–43% [11]. Despite it being a net loss from the system, the remaining materials either in surface-deposited ash or partially combusted biomass remain on site for a period of time before being transferred via water or wind. During this period, a portion of the elements may be captured by plants or immobilized in soil before the excess moves out of the system. Considering the potential for transfer to the atmosphere, it was surprising that we found peak retention of a portion equal to 25.1% C and 92.7% N in the forest floor lost to combustion in the upper 5 cm of soil. Similarly, 48.2% of P and 100.6% Mg was detected in the upper 5 cm of soil, while 87.5% Ca, 96.2% K, 52.1% Mn were detected in the upper 10 cm of soil. Granted the "low intensity" fire reported by Raison, Khanna and Woods [11] had litter temperatures between 600 and 700 °C and flames to 1 m, there still seems to be a large disparity which would imply nearly zero volatilization of forest floor N at the Harrison Experimental Forest. This may be explained in part by the potential nutrient inputs that were not quantified such as: understory, bark, herbaceous plants and erratic coarse woody debris, as well as decomposition of plant roots killed by the fire. In an uneven-aged longleaf, slash pine stand, Lavoie, Starr, Mack, Martin and Gholz [8] reported that 40% of the biomass loss during prescribed fire was associated with aboveground biomass and litter versus 60% from the forest floor, giving some insight to aboveground/belowground mass losses. Another contributing factor may have been reduced plant nutrient demand and uptake during the first 3 months after burning, disrupted the flow of elemental nutrients from soil to plant [29]. Despite the reduction in soil N over the course of 12 months, our results indicate that volatilization of forest floor N was minimal from a dormant season prescribed burn.

In managed southern pine ecosystems, the forest floor is considered a sink for critical pools of otherwise immobilized N and P. Periodic release of nutrients, by fire, mechanical incorporation or fertilization is required to maintain high levels of productivity [40,41]. Longleaf pine does respond to fertilization with N, P, and K, but the species' ability to take advantage of nutrient additions and parlaying it into aboveground biomass is limited compared to the responsiveness of loblolly and slash pines [17]. While longleaf pine are well adapted to soils with low nitrogen availability and low N contents [42], particular regions in the lower Coastal Plain and Gulf Coast are noted for severe P deficiencies and very responsive to P additions [40,43]. We observed a temporary spike in soil P at depths of 0–5 cm and a significant decline from pre-burn levels at depths of 5–10 cm after 12 months, though longer term studies of multiple burn cycles show no effect of fire on soil P [6,44]. Schafer and Mack [24] reported an immediate increase in extractable phosphate after prescribed burning in a palmetto flatwood that returned to pre-burn conditions after 129 days. Foliar P content of palmetto increased over 40% 62 days post-burn, highlighting the rapid response to nutrient availability. In our study, the decline in soil P at depths of 5–10 cm may be demand based, where re-sprouting shrubs and perennial grasses were rapidly growing. More comprehensive monitoring would be needed to ascertain the fate of P and plant availability over time, particularly using resin capture, lysimeters, understory regrowth and foliar analysis.

## 5. Conclusions

Frequent burning is a commonly used tool in longleaf pine stand management and has broad application across the southern United States. We found that prescribed fire consumed most of the forest floor, increased soil pH and caused a pulse of C, N and elemental nutrients to flow in to the near-surface soils. In the initial one to three months post-burn, coinciding with the start of the growing season, retention of nutrients by soil peaked. Most of the N, Ca, K and Mg and roughly 50% of the P and Mn and 25% of the C lost from the forest floor were detected in the soil and apparently not lost to volatilization. By month 12, soil C and N pools declined below pre-burn levels at depths of 5–10 cm, contrary to other examples in southern pine ecosystems. In the upper 5 cm of soil, only Cu remained significantly lower than pre-burn contents by month 12, at depths of 5–10 cm, Cu, Fe, K, Mg, Mn and P remain lower at month 12 than pre-burn contents. We hypothesize that the relatively low soil C stocks, coupled with poor native soil fertility (especially P), created a situation where newly released C and nutrients from the forest floor may have primed existing soil C stocks for decomposition. Testing this hypothesis would require an experimental design with unburnt controls and is beyond the scope of the present study. Burning did not increase soil $C_R$ content, conversely significant declines in $C_R$ occurred and may also be related to decomposition associated with priming. It appears that recovery of soil C and N pools post-burn will require more time on this site than other southern pine forests. Timing burns late in the dormant season so that the pulse of nutrients will coincide with the initiation of growth in the spring may help retention and increase forest productivity.

**Author Contributions:** The concept for this study was developed by J.R.B., while the experimental design and statistical model was jointly conceived by J.R.B., K.H.J. and C.D.N. The statistical analysis and original draft preparation were performed by J.R.B. and review and editing were done by K.J., C.A.M. and C.D.N. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the USDA Forest Service, Southern Research Station.

**Acknowledgments:** Field and laboratory support from Southern Research Station personnel at the Harrison Experimental Forest in Saucier, Mississippi and the Forestry Sciences Laboratory in Research Triangle Park, North Carolina were essential to the success of this project. We specifically thank Joel Burley, Tom Christensen, Bob Eaton, Shelly Hooke, Jason Jackson, Felicia Ogunjube, and Karen Sarsony.

**Conflicts of Interest:** The authors declare no conflict of interest.

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