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Soil chemistry and nutrient regimes following 17–21 years of shortleaf pine-bluestem restoration in the Ouachita Mountains of Arkansas

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Abstract

Harvesting and repeated burning are frequently used to restore shortleaf pine-bluestem ecosystems within the Ouachita Mountains of Oklahoma and Arkansas, USA. These practices have been shown to adequately restore much of the habitat for bird and mammal species that utilize this ecosystem. However, there have been only limited studies to quantify the impact of restoration activities on soil chemistry and nutrient availability in this region. We compared soil chemistry and foliar nutrient concentrations for a 3-year period in three shortleaf pine-hardwood stands that had restoration activities for at least 17 years with soil chemistry and foliar nutrient concentrations in three stands that have had no restoration activities. Mineralizable N, total N, C, Ca, and pH of the surface soil were higher in the restored stands than in the stands without restoration activities. The magnitude of the increases in nutrient concentrations and pH appeared to reflect the combined impacts of harvesting and prescribed burning in the restored stands. Foliar concentrations of N, P, K, and Ca were significantly higher in the restored stands for at least 1 year following the most recent prescribed fire. However, only K concentrations were greater in the restored stands during the entire 3 year study. An increase in nutrient availability within the restored stands suggests that surface soil fertility and productivity may have increased with shortleaf pine-bluestem restoration activities.

Keywords: Fire; Harvesting; Nutrient availability; Foliar chemistry; Restoration

1. Introduction

The Ouachita National Forest (ONF) consists of 690,000 ha in the Ouachita Mountain physiographic region in west central Arkansas and southeastern Oklahoma, USA. The current forest and vegetative communities of the ONF reflect the large scale

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commercial forest harvesting that occurred during the early half of the twentieth century (Smith, 1986) as well as fire suppression activities that followed removal of the last virgin forests in 1930–1940 (Smith, 1986; Bukenhofer and Hedrick, 1997). Harvests of the virgin forest typically removed shortleaf pine (*Pinus enchinata* Mill.) to a 35.5 cm diameter stump limit and high quality oak trees (Shelton and Murphy, 1991). Shortleaf pine still dominates the overstory component of the second growth forests (Shelton and Murphy, 1991). However, second growth shortleaf pine forests generally have much higher densities and a greater hardwood component than the virgin shortleaf pine forests (Shelton and Murphy, 1991; Foti and Glenn, 1991). The understories of these second growth forests are also dominated by woody understory vegetation, rather than the forbs and grasses such as big and little bluestem grass (*Andropogon gerardii* and *Schizachyrium scoparium*) that were typically found in the more open virgin shortleaf pine stands (Nuttall, 1981; Cogburn, 1976; Bukenhofer et al., 1994; Masters et al., 1995) that were frequently burned. In an effort to provide habitat for red-cockaded woodpeckers (*Picoides borealis*) and other biota that favor these more open and grass/forb dominated habitats, the ONF is currently restoring shortleaf pine-bluestem grass (SPBG) ecosystems to a portion of this region (Bukenhofer et al., 1994; USDA Forest Service, 1996; Bukenhofer and Hedrick, 1997).

Restoration of this ecosystem entails reducing tree basal area through thinning and the reintroduction of prescribed fires into the ecosystem. During initial SPBG restoration, target pine and hardwood basal areas are approximately 13.7 and 2.3 m^2/ha, respectively (USDA Forest Service, 1996). Application of fire to control woody understory development and enhance herbaceous vegetation usually occurs at 3–4 year intervals during the dormant season (Masters et al., 1996; Sparks et al., 1998).

The long-term effect of these restoration activities on soil characteristics and nutrient regimes has not been sufficiently quantified. Long-term, repeated applications of fire have been found to alter nutrient regimes, soil chemistry, and soil physical characteristics (McKee, 1982, 1991; Binkley, 1986; Binkley et al., 1992; Bell and Binkley, 1989). Masters et al. (1993) also found an increase in NO_3-N, Ca, and P contents of soil following initial harvesting an prescribed fires in shortleaf pine-hardwood stands i Oklahoma. To what degree the change in nutrient observed by Masters et al. (1993) persists with long term applications of fire or to what extent harvesting i these restored stands impacted soil nutrient regimes i unknown. Modification of the pine-hardwood com position of a stand in the Ouachita Mountains has bee found to alter cycling and fluxes of some nutrients, a much as 10 years following harvesting and hardwoo removal (Liechty et al., 2002).

To better understand and evaluate the effects o long-term shortleaf pine-bluestem restoration activ ities on soils and nutrient availability, we compare soil chemistry and shortleaf pine foliage nutrien concentrations in stands that had experienced SPBG restoration activities for 17–21 years with stands tha had no management activities during this time period Our objectives were to (1) determine if soil chemistr or nutrient availability had been altered by SPBG activities and (2) evaluate if there has been any declin in soil productivity.

2. Methods

2.1. Study design

Six individual shortleaf pine-hardwood stands 1- 10 ha in size were used for the study. Three stands ha not received any restoration or silvicultural activitie during the last 40 years and were typical close canopy shortleaf pine-hardwood stands (control). Th other three stands were restored SPBG stands. Th restoration prescription for the SPBG stands specifie the retention of 14–16 m^2/ha of overstory basal area i pines and hardwoods; of this, 10–30% (if available was to be in mast-producing hardwoods and th balance $\geq$70% in shortleaf pine. The prescription also called for the felling of all midstory hardwoods except fruiting shrubs, and the use of dormant seaso prescribe fires on a 3–5-year interval. Pine harvest were conducted using commercial timber sale according to standard USDA Forest Service proce dures. The majority of mid- and overstory hardwood that were felled in a stand were left on the ground du to poor hardwood markets. The initial overstory treatments occurred between 1978 and 1979 while th midstory treatments occurred in 1980 on two SPBG stands (1 and 3) and in 1990 on the other SPBG stand (2). In stands 1 and 3, prescribed fires were applied every 3–4 years beginning in 1980 or 1982. In stand 2, prescribed fires were applied in 1978, 1989, 1992, 1994, and 1997. The last prescribed fire at all three SPBG stands occurred during March of 1997 prior to the initiation of the study. It was assumed that conditions and characteristics of the six stands were similar prior to the initiation of SPBG restoration activities. This assumption was thought to be reasonable given the proximity and similarity in site and physiographic conditions.

2.2. Study site location and description

The stands occurred on either the Carnasaw or Sherless soils series (NRCS, 1998). These two series have similar characteristics and are common throughout the Ouachita National Forest and Ouachita Mountains. The Carnasaw series is classified as a clayey, mixed, mesic, thermic, Typic Hapludult and is generally 100–150 cm deep overlying a soft shale bedrock (NRCS, 1998). The Sherless series is a fine-loamy, mixed, thermic, Typic Hapludult which is 50–100 cm deep overlying a soft sandstone bedrock (NRCS, 1998). All stands had loamy surface textures, had similar surface soil (35–50%) and subsurface soil (35–40%) rock contents, were located on 10–20% slopes in southern or southwestern aspects at elevations between 237 and 317 m above MSL. The six stands are located within a 5–7 km radius at approximately 34°47′N latitude and 94°47′W longitude.

In the fall of 1997, one 0.5–1.0 ha circular plot was established in each stand. These plots were selected such that the soil, vegetation, and landscape characteristics within the plot were similar to the soil, vegetation, and landscape characteristics of the stand as a whole. In each plot, four 25–35 m diameter subplots were established. Sizes of subplots for a given stand were dependent on the size of the plot selected for sampling in each stand. One subplot was established at the center of the main plot while the centers of the other three subplots were located 30–50 m from the center of the first such that perimeters of the four subplots did not intersect. Average plot basal area (trees > 8.9 cm) as well as dominant and codominant ages and heights of shortleaf pine measured in 1998 in each stand are presented in Table 1. Post oak (*Quercus stellata* Wangenh.) dominated the hardwood overstory but white oak (*Quercus alba* L.), black oak (*Quercus vetutina* Lam.), and mockernut hickory (*Carya tomentosa* Nutt.) also occurred in at least one of the six stands.

Table 1
Mean (standard deviation) of pine basal area and hardwood basal area as well as mean (standard deviation) age and height of shortleaf pine dominant and codominate trees measured during the fall of 1998 in the three shortleaf pine-bluestem grass (SPBG) and three unaltered shortleaf pine-hardwood (control) stands in the Ouachita Mountains of Arkansas

	Stand 1	Stand 2	Stand 3
Pine basal area (m^2/ha)			
Control	20.7 (4.2)[a]	29.8 (9.7)	22.4 (3.9)
SPBG	15.5 (3.9)	16.6 (3.4)	15.5 (4.3)
Hardwood basal area (m^2/ha)			
Control	8.0 (1.3)	7.5 (2.2)	9.8 (7.1)
SPBG	0.6 (1.1)	10.9 (5.7)	0.0 (0.0)
Age (year) of dominant and codominant pine			
Control	77 (2.1)[b]	79 (7.0)	80 (2.2)
SPBG	88 (7.6)	84 (7.2)	90 (2.1)
Height (m) of dominant and codominant pine			
Control	19.6 (0.9)	23.4 (1.5)	22.4 (0.9)
SPBG	25.1 (1.0)	20.4 (0.8)	24.3 (0.2)

[a] Basal area determined by point sampling and a BAF 10 prism.
[b] Age computed by counting growth rings at a height of 1.37 m and assuming trees required 5 years to reach a height of 1.37 m.

2.3. Soil sampling and analysis

Individual annual composite soil samples were collected from five evenly spaced locations within each subplot during the fall of 1997, 1998, and 1999. Each soil sample was collected by using a sharpshooter shovel to remove an approximate 13 cm × 13 cm plug of mineral soil to a depth of 15 cm. This method of soil removal was used due to the high volume of rocks. After plug removal, the sides were shaved using a knife to remove any contaminants, and then the upper 0–5 cm and the lower 5–15 cm samples were removed. All five samples from a subplot and depth were composited, homogenized, placed in a bag, and returned to the lab. Soils were then air-dried and sieved through a 2 mm screen. Soil analysis was performed on the 0–5 cm and a composited 0–15 cm sample. To obtain a composited sample from the top 15 cm of surface soil, a portion of the soil from the 0–5 cm and 5–15 cm depths were combined on a 1:2 volume basis and homogenized for each subplot and collection year. It was assumed that rock content and bulk density of the two soil depths was similar and that remixing of these soils would produce similar samples to those before separation. Due to budget constraints not all soil parameters were quantified for the 0–5 cm of soil and thus these analyses were not included in the results.

Soil pH (1:2 soil:water ratio) calculated CEC, base saturation, and soil organic matter concentration (Walkley and Black, 1934) were determined for each soil sample. Concentrations of P, K, Ca, Mg, and S were determined using ICP analysis after a modified Melich III extraction (Mehlich, 1984). Total N and C were determined by combustion using a Leco-2000 CN analyzer for only the soils collected in 1999. Mineralizable N (Powers, 1980) was determined for soil samples from each of the 3 years.

2.4. Foliage sampling and analysis

In the fall of 1997, 1998, and 1999, current year foliage was collected using a shotgun from the top third of the crown of five separate dominant or co-dominant shortleaf pine trees in each subplot. Foliage was returned to the laboratory and composited by subplot for each year. Samples were placed in a forced air oven and dried at 65 °C for 72 h or until there was no change in mass. Average fascicle mass and length was then determined from 50 randomly selected fascicles in 1997 and 100 randomly selected fascicles in 1998 and 1999 from each subplot. The foliage was then ground to pass through a 2 mm screen. P, K, Ca, Mg, and S concentrations were determined by ICP after a perchloric digestion (Alder and Wilcox, 1985). N was determined colormetrically after using a micro-Kjeldhal digestion technique (Bremner, 1996).

2.5. Statistical analysis

Since mineral soil and foliage was collected from the same stands and subplots in each of 3 years, a repeated measurement ANOVA was used to determine if soil or foliar attributes differed among treatment (SPBG versus control), years (1997–1999), and/o treatment × year interactions. If differences amon years or treatment × year interactions were sig nificant, means were separated using a Tukey's HSI test. The stand (the 0.5–1 ha measurement plot withi the stand) was considered the experimental unit in th study. Measurements from the subplots were con sidered subsamples of the experimental unit. Pearson' correlation coefficients were used to quantify relation ships among various soil, foliage, stand, and abioti factors. All tests were performed at $\alpha = 0.05$ excep where noted in results.

3. Results

3.1. Soil

Chemistry of the surface 15 cm of mineral soil differed in the two stand types. The pH and C concentrations were significantly higher in the SPBC stands than in the control stands (Table 2). Averag concentrations of Ca were approximately 60% greater i the SPBG stands than the control stands (Table 2) Differences in pH and Ca concentrations between stan types were similar during the 3-year period (Fig. 1A an B) and stand type × year interactions were no significant. Although concentrations of Ca were greate in the SPBG stands, concentrations of other bas cations, as well as base saturation, were similar in th two stand types (Table 2). CEC, P concentrations, and S concentrations also did not differ significantly betwee the two stand types. Soil pH was most strongl correlated with base saturation ($r = 0.672$, $P < 0.01$ and Ca concentrations ($r = 0.693$, $P < 0.01$).

Mineralizable N measured within the SPBG stand was approximately 19% greater than in the contro stands (Table 2). Although site × year interaction were not significant ($P = 0.40$), mineralizable N concentrations tended to increase slightly in th control stands but fluctuated in the SPBG stand during the 3 year study (Fig. 1C). Mineralizable N was positively correlated with soil pH ($r = 0.409$ $P < 0.01$), CEC ($r = 0.319$, $P = 0.01$), base saturatio ($r = 0.417$, $P < 0.01$), and Ca concentration ($r = 0.412$, $P < 0.01$) but was not significantl correlated with any other soil parameter.

Table 2
Mean values for selected surface soil (0–15 cm) parameters measured during the fall of 1997–1999 within three shortleaf pine-bluestem grass (SPBG) and three unaltered shortleaf pine hardwood (control) stands in the Ouachita Mountains of Arkansas

	SPGB	Control	*P*-value
pH	5.28 (0.16)[a]	4.91 (0.15)	0.01
CEC (cmol/kg)	7.8 (0.6)	7.2 (0.3)	0.12
Base saturation (g/kg)	469 (45)	407 (19)	0.10
Organic matter (g/kg)	36.2 (1.9)	33.0 (3.6)	0.10
C (g/kg)[b]	25.6 (1.3)	19.8 (0.9)	0.03
C:N[b]	20.9 (1.4)	17.9 (1.1)	0.02
TKN (g/kg)[b]	1.2 (<0.1)	1.1 (0.1)	0.04
Mineralizable N (mg/kg)	59.8 (3.4)	50.4 (4.8)	0.01
P (mg/kg)	6.2 (0.8)	7.0 (1.5)	0.38
K (mg/kg)	76.0 (7.1)	66.1 (8.2)	0.14
Ca (mg/kg)	533 (104)	332 (47)	0.03
Mg (mg/kg)	117 (16)	134 (37)	0.52
S (mg/kg)	8.0 (1.7)	10.1 (1.3)	0.11

[a] Values in parentheses are standard deviations.
[b] Measurements only from the fall 1999 sample collection.

Concentrations of mineral soil C, total N, and C:N ratios in 1999 were significantly greater in the SPBG stands than in the control stands (Table 2). Mineral soil C concentrations in 1999 were on average 30% greater in the SPBG stands than the control stands. Although levels of organic matter did not significantly differ among stand types for any year, numerically the differences were greatest in 1999 when C concentrations were significantly different. If only the 1999 organic matter concentrations were tested, then differences between stand types for this soil characteristic were significant ($P = 0.02$). However, organic matter concentrations in the SPBG stands were approximately 16% higher than those in the control while differences in C were 30% higher.

Mean subplot concentrations of mineralizable soil N ($r = -0.518$, $P = 0.01$), Ca ($r = -0.688$, $P < 0.01$), total N ($r = -0.519$, $P = 0.01$), K ($r = -0.509$, $P = 0.01$), and C ($r = -0.718$, $P < 0.01$) as well as soil pH ($r = -0.686$, $P < 0.01$), CEC ($r = -0.750$, $P < 0.01$), base saturation ($r = -0.681$, $P < 0.01$), and C:N ratios ($r = -0.680$, $P < 0.01$) were found to be significantly and negatively correlated with the subplot total tree basal area. However, these correlations generally reflected the differences in basal area of the two treatments and not the variation within the individual treatments (for example, Fig. 2A–C). For example K concentrations of the control subplots were negatively correlated with total tree basal area ($r = -0.644$, $P = 0.02$) but K concentrations of the SPBG subplots were positively ($r = 0.632$, $P = 0.03$) correlated with total tree basal area. CEC and base saturation were negatively and significantly correlated with total tree basal area in the SPBG subplots but not the control plots.

3.2. Foliage

Differences in shortleaf pine foliage nutrient concentrations were also evident in the two stand types. However, these differences were frequently not consistent among years and stand type × year interactions were significant for a number of foliar measurements (Table 3). None of the nutrients tested were consistently greater in the control compared to SPBG stands. Only concentrations of K were consistently greater in the SPBG than the control stands during each year of the study. However, foliar K concentrations in the control were only 9–10% less than in the SPBG stands. Foliar concentrations of N, P, and S were significantly higher in the SPBG stand than the control stands during 1997 but concentrations of P and S were similar in the two stand types in 1998 and 1999 while concentrations of N were significantly greater in the control than the SPBG stands in 1998 (Table 3).

Concentrations of nutrients in foliage did not appear to be strongly related to the concentrations of the corresponding nutrients in the mineral soil. For the majority of nutrients, foliar and mineral soil con-

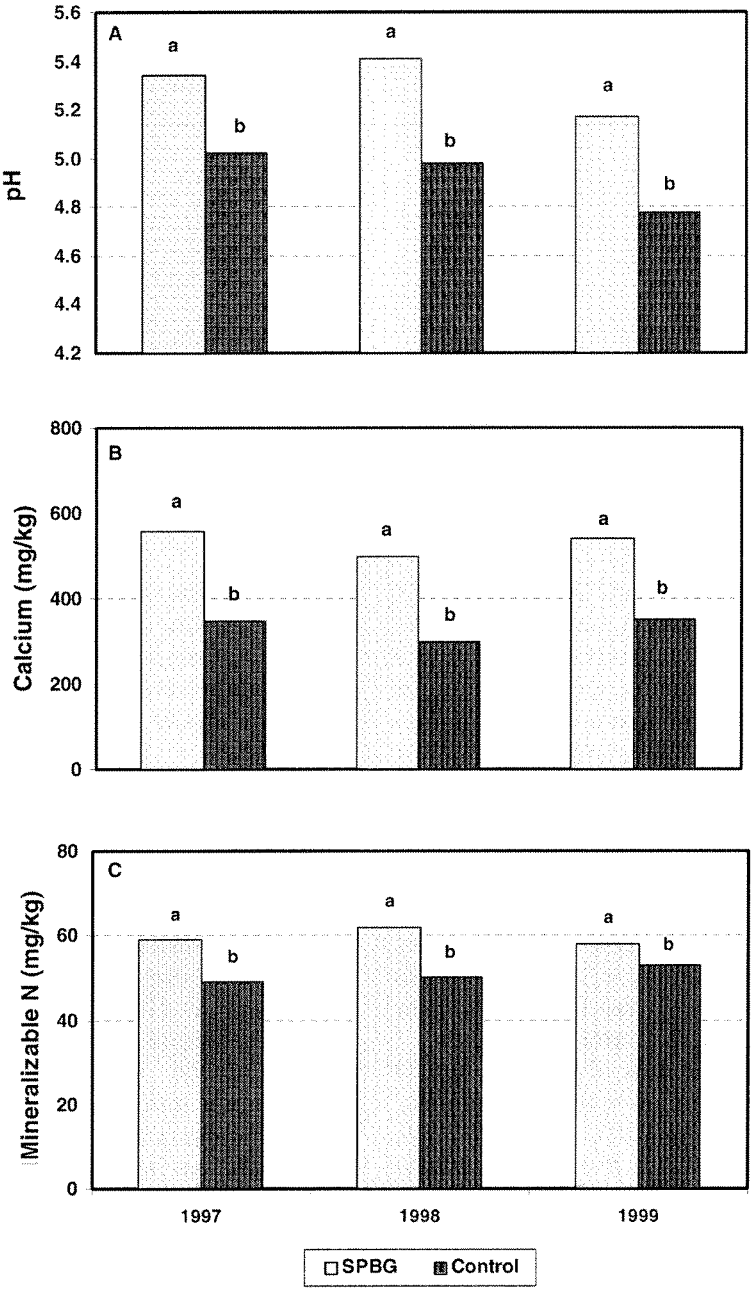

Fig. 1. Mean pH (A), Ca concentration (B), and mineralizable N (C) from surface soils (0–15 cm) collected during 1997–1999 from three shortleaf pine-bluestem grass (SPBG) and three unaltered shortleaf pine-hardwood (control) stands in the Ouachita Mountains of Arkansas (Bars with the same letter for a given year and soil parameter are not significantly different at $\alpha = 0.05$).

centrations were not significantly correlated. However, Mg concentrations of foliage and mineral soil were positively correlated when both control and SPBG stands were analyzed together ($r = 0.404$, $P < 0.01$) but not when only the SPBG stands were included in the analysis ($r = 0.101$, $P = 0.57$). Foliar

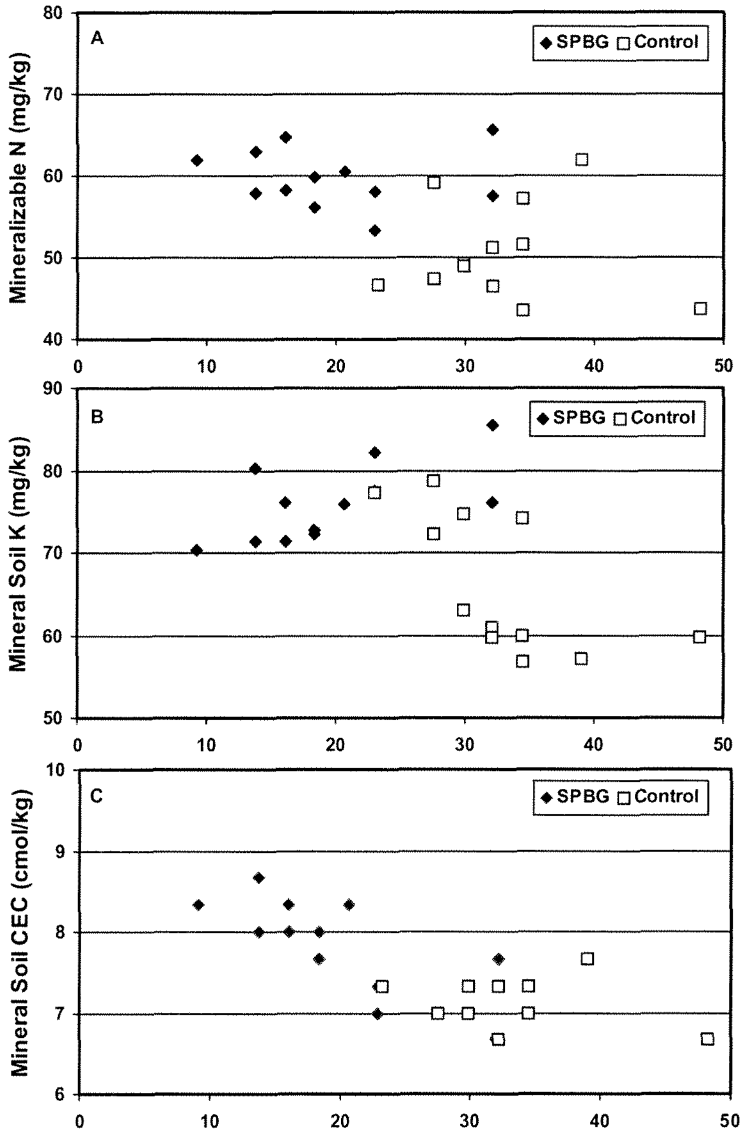

Fig. 2. Mean plot surface mineralizable soil N concentrations (A), K concentrations (B) and soil CEC (C) during 1997–1999 vs. 1998 plot basal area in three shortleaf pine-bluestem grass (SPBG) and three unaltered shortleaf pine-hardwood (control) stands in the Ouachita Mountains of Arkansas.

concentrations of P were found to be negatively correlated with mineral soil concentrations of P in the combined control and SPBG data set ($r = -0.320$, $P = 0.01$) as well as when only the SPBG stands were included in the analysis ($r = -0.336$, $P = 0.05$). Although foliar concentrations of K were not significantly correlated with mineral soil K concentrations ($r = 0.076$, $P = 0.53$) when all 3 years were included in the analysis, foliar K concentrations were significantly correlated with mineral soil K in 1997 ($r = 0.429$, $P = 0.04$) but not in 1998 ($r = 0.389$, $P = 0.06$) or 1999 ($r = 0.168$, $P = 0.44$).

Mean foliar concentrations of P, K, and S were significantly correlated with total plot basal area when

Table 3
Mean foliage nutrient concentrations collected during 1997–1999 from shortleaf pine dominate and codominate trees in three shortleaf pine-bluestem grass (SPBG) and three unaltered shortleaf pine hardwood (control) stands in the Ouachita Mountains of Arkansas

	1997		1998		1999	
	SPBG	Control	SPBG	Control	SPBG	Control
N (g/kg)	12.5a*	11.4b	13.4b	14.2a	13.3a	13.8a
P (g/kg)	0.9a	0.8b	1.1a	1.1a	1.0a	1.0a
K (g/kg)	4.0a	3.6b	4.5a	4.2b	4.4a	4.0b
Ca (g/kg)	2.5a	2.2a	2.0a	2.1a	2.3a	2.4a
Mg (g/kg)	1.2a	1.2a	1.1a	1.3a	1.3a	1.4a
S (g/kg)	0.75a	0.67b	0.87a	0.89a	0.77a	0.75a

* Treatments for a given year and a specific foliar nutrient concentration with the same letter are not significantly different at the $\alpha = 0.05$.

data from both the SPBG and control were analyzed together ($r = -0.424$, $P = 0.04$, $r = -0.595$, $P = 0.02$, $r = -0.499$, $P = 0.01$). However like mineral soil parameters, correlations generally reflected the differences in basal area of the two treatments and not the variation within treatments.

4. Discussion

Assuming that the soils of the two stand types were similar before restoration activities began; results from this study indicate that shortleaf pine-bluestem restoration activities have altered soil nutrient levels and soil chemistry. One of the most pronounced changes was the increase of surface soil pH and Ca concentrations in the SPBG stands. Increases in soil Ca and pH have typically been observed following long-term use of prescribed fires in southern pine stands (McKee, 1991; Binkley et al., 1992). In addition increases in Ca have been found following harvesting activities in hardwood or mixed pine hardwood stands. Johnson and Todd (1998) reported elevated levels of Ca in surface soil 15 years following a sawlog harvest in a mixed oak stand. They attributed this increase to the decomposition of residues from the harvest. Liechty et al. (2002) reported that Ca levels of surface soils, collected 10 years after a harvest that retained 13.8 m^2/ha of pine basal area but removed or deadened all hardwood trees, was significantly greater than in surface soils collected from an unharvested shortleaf pine-hardwood stand.

Initial thinning and midstory reduction treatments used for SPBG restoration adds large amounts of woody debris, organic matter, and nutrients to the soil surface. Seifert (2004) reported that initial harvesting and midstory control treatments during SPBG restoration of a sub-watershed in the Ouachita Mountains added a total of 88.1 mg/ha of woody debris containing 139 kg/ha of Ca to the forest. The large additions of woody debris and Ca to the forest floor were due to the poor markets for the hardwoods and thus the retention of these trees on site after felling (Seifert et al., 2004). Decomposition of the woody debris would add large amounts of Ca as well as other nutrients and organic matter to the soils of the SPBG stands.

Together these two treatments, fire and harvesting, appear to alter soil Ca levels to a greater degree than the treatments individually. Masters et al. (1993) found that Ca, Mg, and K in soil increased only slightly if harvesting was not followed by a prescribed fire or prescribed fire was not proceeded by some type of harvesting activity in shortleaf pine-hardwood stands. However, when harvesting and prescribed fire was combined Ca, Mg, and K concentrations in surface soils significantly increased (Masters et al., 1993). Although we found no significant increase in Mg or K, we believe that the combination of harvesting with the retention of large amounts woody debris and prescribed fire were responsible for the over 60% increase in surface soil Ca concentrations observed in the SPBG stands. The lack of significant stand type × year interactions for Ca and pH during the three study period (Fig. 1A and B) further indicates that differences between the stand types have remained relatively constant and are not solely related to the most recent prescribed fire in 1997.

Increases in organic matter, N, and C were also evident in the soils of the SPBG stands. Like Ca increases of C and N have been found following harvesting. Knoepp and Swank (1997) as well as Johnson and Todd (1998) found increases of surface soil C and N for as much as 12–15 years following commercial sawlog harvesting in mixed oak and mixed hardwood stands. The increases of soil C and N in these studies were attributed to inputs from harvesting residues (Knoepp and Swank, 1997; Johnson and Todd, 1998), root mortality (Knoepp and Swank, 1997), and/or an increase in herbaceous and N-fixing plants (Knoepp and Swank, 1997). In a review of forest management effects on soil C and N, Johnson and Curtis (2001) reported that sawtimber harvesting in conifer stands significantly increased A horizon N and C on average between 24 and 26%. No doubt, additions of woody debris during harvesting and competition control within the SPBG stands contributed to the increases of organic matter, N, and C in the surface soils.

The impacts of fire on soil C and N can vary. Previous studies quantifying the effects of periodic prescribed fires have indicated significant losses (Wright and Hart, 1997; Bell and Binkley, 1989), neither significant losses nor gains (Moehring et al., 1966; Binkley et al., 1992; Waldrop et al., 1987), or slight increases of total N (McKee, 1991) following long-term use of periodic fires. The amount of legumes generally increases following SPBG restoration and could increase the amount of N in the soil. Masters (1991a) observed an approximate 22-fold increase of grasses, forbs, and legume mass 4 years following a combination of harvesting and burning treatments within shortleaf pine-hardwood stands. Coverage of legumes was found to be 5–9 times greater in treatments that included pine harvesting, hardwood competition control, and 2–3 year burning regimes (Masters, 1991b) than in the controls. Additions of N from legumes in southern pine stands can be significant. Hendricks and Boring (1999) found that a dense population of legumes fixed 7–9 kg N/ha 2–3 years following the clearcutting of two loblolly pine stands that had been burned on a 4–5 year interval during the prior rotation.

The increased mineralizable N in the soils of the SPBG during the entire 3 year study is perhaps the most unique change in the soils. A number of studies have shown that mineralizable N can increase for short periods of time (<1 year) following prescribed fires (White, 1986; Schoch and Binkley, 1986; Knoepp and Swank, 1995; Monleon et al., 1997; Deluca and Zouhar, 2000) but long-term changes in mineralizable N have rarely been documented. Frequently, mineralizable N levels one or more years after fire are lower than in unburned areas (Vance and Henderson, 1984; Schoch and Binkley, 1986; Monleon et al., 1997; Deluca and Zouhar, 2000). Morris and Boerner (1998) found N mineralization was higher in harvested than unharvested oak stands in Indiana but long-term studies following partial harvesting in other forest communities have not found significant changes in N mineralization (Kranabetter and Coates, 2004).

The elevated levels of mineralizable N in the SPBG stands could be a result of the elevated pH and Ca concentrations. Soil acidity can limit activity of some microorganisms (Fisher and Binkley, 2000) but N mineralization has frequently not been found to decrease with decreases in soil acidity (Lohm et al., 1984; Morris and Boerner, 1998). However, increased levels of Ca in soil may directly influence mineralizable N. Martinez and Perry (1997) found that available N within soils of Douglas-fir stands was strongly related to soil Ca levels, but not soil pH. They suggested that available N may have increased with Ca levels because decomposer organisms were Ca limited or that the high levels of Ca in the soil increased granulation and thus physical soil quality. Increases in N mineralization and nitrification in oak stands in Indiana that had previously been harvested compared to stands that had never been harvested were found to be related to increases in soil Ca:Al ratios (Morris and Boerner, 1998). To what degree the increase of Ca following restoration activities has increased mineralizable N is unknown. However, mineralizable N in the surface soils of the control and SPBG stands was most strongly correlated with Ca levels, and not significantly correlated with other macronutrient concentrations, C:N ratios, or organic matter concentrations. If the increased levels of Ca are responsible for the increases in mineralizable N, the greater levels of mineralizable N in the SPBG stands most likely reflect the increases of Ca attributed to the combined harvesting and burning treatments in these stands.

The higher levels of foliar N, P, K, and S observed in the SPBG stands appear to be related to the restoration activities that have occurred in these stands. Higher concentrations of foliar N, P, or K in canopy trees have been found shortly following prescribed fires (James and Smith, 1977; Gillion et al., 1999) and for longer periods (2–9 years) following thinning or partial stand harvesting (Pang et al., 1987; Mugasha et al., 1991; Velazquez-Martinez et al., 1992).

The higher current year foliage concentrations of N, P, and S in the SPBG stands compared to the control stands during 1997, but not 1998 or 1999, suggests that alterations in these concentrations were due to a short-term increase in N, P, and S availability following the prescribed fire in March of 1997. The increases in availability of P and S appear transient since concentrations in soils did not significantly differ between stand types during the fall of 1997. Short-term (1.5–7 months) increases of readily available forms of soil phosphorus such as soluble P and bicarbonate extractable P have been observed by Gifford (1981), Kutiel and Naveh (1987) and/or Debano and Klopatek (1988) following fire. It has been proposed that this readily available P is quickly lost from surface soils because it is leached into lower soil depths (Kutiel and Naveh, 1987), absorbed by $CaCO_3$ (Debano and Klopatek, 1988), or precipitated into insoluble Ca forms (Debano and Klopatek, 1988). It seems likely that plant available soil P was increased by the March 1997 fire and that at least a portion of this P was absorbed by the shortleaf pine shortly following the fire. After this point, readily available P levels decreased in the soil and had no further impact on foliar concentrations of P.

Although mineralizable N levels were higher in the soils of the SPBG stands than in the control stands for the entire 3 years of study, foliar concentrations of N in the SPBG stands were only higher than the control stands during the first year of the study. As indicated by correlation analysis, mineralizable N and foliar N concentrations were not significantly correlated. The poor relationships between these two N parameters may indicate that mineralizable N is a poor indicator of N availability in these stands following fires. Increases of NH_4^+, and thus available N, following fires can occur from soil heating or mineralization of organic N directly by the fire (Fisher and Binkley, 2000); processes that would be poorly represented by anaerobic incubation methods used to estimate the mineralizable N levels. An increase in NH_4^+ immediately following the fire may explain the higher foliar levels of N in the SPBG compared to control stands in 1997.

Although average soil and foliar K concentrations were higher in the SPBG stands than the control stands, foliar K concentrations were only significantly and positively correlated with soil K concentrations in 1997. The lack of a significant correlation of foliar K with surface soil K in 1998 and 1999 suggests that surface soil concentrations of K had little impact on foliar K concentrations in the second and third years following the prescribed fires. K is a mobile nutrien[t] and any increases of K to the surface soil from fire i[n] the SPBG stands could have leached below the surfac[e] soil thereby limiting the impact of surface soil K o[n] foliar K in 1998 and 1999. The accumulations of K below the surface soil depth of 15 cm may still b[e] available for tree uptake, and thus be responsible fo[r] the elevated concentrations of K in foliage of th[e] SPBG stands during the entire 3 year study period.

Our study indicated that it was unlikely tha[t] restoration activities have reduced nutrient availabilit[y] or fertility, and thus productivity attributed to nutrien[t] availability of the SPBG stands, over at least a tw[o] decade period of restoration. Foliar and surface soi[l] nutrient levels in the SPBG stands were similar o[r] higher than those in the controls. It is possible that th[e] SPBG restoration activities have increased th[e] productivity of the surface soil because mineralizabl[e] N, Ca, total N, C, and pH was significantly higher i[n] the SPBG stands than in the control stands.

To better evaluate the effect of SPBG restoration o[n] shortleaf pine nutrient status and thus productivity, w[e] compared foliar nutrient concentrations to critica[l] concentrations. Since we could not find any publishe[d] critical concentrations for shortleaf pine foliage, w[e] compared the foliar nutrient concentrations from th[e] sampled shortleaf pine to critical concentrations fo[r] loblolly pine (*Pinus taeda* L.). Concentrations of N, P, and Ca in both the control and SPBG stands wer[e] above loblolly pine critical concentrations summarized by Ngono and Fisher (2001) or reported by Fishe[r] (1981). P was potentially the most limiting nutrient i[n] these stands. Foliar concentrations of P in 1997 wer[e] below the deficient critical value of 1.0 g/kg summarized by Ngono and Fisher (2001) for loblolly pine. Concentrations of P in 1998 and 1999 were also in th[e] range indicated as marginal by Ngono and Fishe[r] (2001) or responding to P fertilizer my Schultz (1997). Concentrations of K in the shortleaf pine foliag[e] within both the control and SPBG stands were in th[e] marginal range for loblolly pine as indicated by Ngono and Fisher (2001). Regardless of the nutrient considered, restoration activities did not appear to significantly rectify any potential deficiencies within these shortleaf pine stands. Increases in foliar concentrations of P and/or K as a result of SPBG activities did not likely increase concentrations to the point where they would be considered satisfactory in the SPBG stands while unsatisfactory in the control stands.

5. Conclusions

Shortleaf pine-bluestem restoration can alter nutrient availability within surface soils. This study showed that pH, Ca, total N, C, and C:N ratios were increased by approximately 20 years of restoration activities. Concentrations of N, P, K, and S in shortleaf pine foliage were also elevated immediately following the last prescribed fire in the restored stands. However, increases in N, P, and S were temporary and by the second year after the fire differences between restored and control areas were not evident. The combination of harvesting, midstory reductions, and prescribed fire, rather than any one individual restoration technique, was most likely responsible for the relatively large changes in surface chemistry observed in this study. There appeared to be no negative impact on nutrient regimes in these stands that would have reduced productivity of the shortleaf pine growing in the restored stands.

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References

Alder, P.R., Wilcox, G.E., 1985. Rapid perchloric acid digest methods for analysis of major elements in plant tissue. Comm. Soil Sci. Plant Anal. 16, 1153–1163.

Bell, R., Binkley, D., 1989. Soil nitrogen mineralization and immobilization in response to periodic prescribed fire in a loblolly pine plantation. Can. J. For. Res. 19, 816–820.

Binkley, D., 1986. Soil acidity in loblolly pine stands with interval burning. Soil Sci. Soc. Am. J. 50, 1590–1594.

Binkley, D., Richter, D., David, M.B., Caldwell, D., 1992. Soil chemistry in a loblolly/longleaf pine forest with interval burning. Ecol. Appl. 2, 157–164.

Bremner, J.M., 1996. Nitrogen-total. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnson, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis. Part 3, vol. 5. Soil Science Society of America Book Series, pp. 595–624.

Bukenhofer, G.A., Hedrick, L.D., 1997. Shortleaf pine/bluestem grass ecosystem renewal in the Ouachita Mountains. In: Wadsworth, K.G. (Ed.), Transaction of the Sixty-Second North American Wildlife and Natural Resources Conference, Washington, DC, 14–18 March, pp. 509–515.

Bukenhofer, G.A., Neal, J.C., Montague, W.G., 1994. Renewal and recovery: shortleaf pine/bluestem grass ecosystem and red-cockaded woodpeckers. Proc. Arkansas Acad. Sci. 48, 243–245.

Cogburn, M., 1976. Whittler by the roadside. The Looking Glass: Reflecting Life In The Ouachitas 2 (8), 3–4.

Debano, L.F., Klopatek, J.M., 1988. Phosphorus dynamics of pinyon-juniper soils following simulated burning. Soil Sci. Soc. Am. J. 52, 271–277.

Deluca, T.H., Zouhar, K.L., 2000. Effects of selection harvest and prescribed fire on the soil nitrogen status of ponderosa pine forests. For. Ecol. Manage. 138, 263–271.

Fisher, R.F., 1981. Soils interpretations for silviculture in the southeastern Coastal Plain. In: Barnett, J. (Ed.), Proceedings of the First Biennial Southern Silvicultural Research Conference, Atlanta, GA, 6–7 November 1980. USDA For. Serv. Gen. Tech. Re SO-GTR-34, pp. 323–330.

Fisher, R.F., Binkley, D., 2000. Ecology and Management of Forest Soils, third ed. Wiley, New York, 487.

Foti, T.L., Glenn, S.M., 1991. The Ouachita Mountain landscape at the time of settlement. In: Hendeson, D., Hedrick, L.D. (Eds.), Proceedings of the Conference on Restoration of Old Growth Forests in the Interior Highlands of Arkansas and Oklahoma, Ouachita Nat. For. Winrock Intern. Inst., Morrilton, AR, 19–20 September, 1990, pp. 49–65.

Gifford, G.F., 1981. Impact of buring pinyon-juniper debris on select soil properties. J. Ranage Manage. 34, 357–359.

Gillion, D., Houssard, C., Valette, J.C., Rigolot, E., 1999. Nitrogen and phosphorus cycling following prescribed burning in natural and managed Aleppo pine forests. Can. J. For. Res. 29, 1237–1247.

Hendricks, J.J., Boring, L.R., 1999. N_2-fixation by native herbaceous legumes in burned pine ecosystems of the southeastern United States. For. Ecol. Manage. 113, 167–177.

James, T.D.W., Smith, D.W., 1977. Short-term effects of surface fire on the biomass and nutrient standing crop of *Populus tremuloides* in southern Ontario. Can. J. For. Res. 7, 666–679.

Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. For. Ecol. Manage. 140, 227–238.

Johnson, D.W., Todd Jr., D.E., 1998. Harvesting effects on long-term changes in nutrient pools of mixed oak forest. Soil Sci. Soc. Am. J. 62, 1725–1735.

Knoepp, J.D., Swank, W.T., 1995. Comparison of available soil nitrogen assays in control and burned forested sites. Soil Sci. Soc. Am. J. 59, 1750–1754.

Knoepp, J.D., Swank, W.T., 1997. Forest management effects on surface soil carbon and nitrogen. Soil Sci. Soc. Am. J. 61, 928–935.

Kranabetter, J.M., Coates, K.D., 2004. Ten-year postharvest effects of silviculture systems on soil-resource availability and conifer nutrition in a northern temperate forest. Can. J. For. Res. 34, 800–809.

Kutiel, P., Naveh, Z., 1987. The effect of fire on nutrients in a pine forest soil. Plant Soil 104, 269–274.

Liechty, H.O., Sawyer, V.L., Shelton, M.G., 2002. Alteration of nutrient status by manipulation of composition and density in a shortleaf pine-hardwood stand. In: Outcalt, K.W. (Ed.), Proceedings of the Eleventh Biennial Southern Silviculture Research Conference, Knoxeville, TN, 20–22 March 2001. USDA For. Serv. Gen. Tech. Re SRS-GT-48, pp. 10–15.

Lohm, U., Larsson, K., Nômmik, H., 1984. Acidification and liming of coniferous forest soil: long-term effects on turnover rates of carbon and nitrogen during an incubation experiment. Soil Biol. Biochem. 16, 343–346.

Martinez, A.V., Perry, D.A., 1997. Factors influencing the availability of nitrogen in thinned and unthinned Douglas-fir stands in the central Oregon Cascades. For. Ecol. Manage. 93, 195–203.

Masters, R.E., 1991a. Effects of timber harvest and prescribed fire on wildlife habitat and use in the Ouachita Mountains of eastern Oklahoma. Ph.D. Thesis. Oklahoma State University, Stillwater, p. 330.

Masters, R.E., 1991b. Effects of fire and timber harvest on vegetation and cervid use on oak-pine sites in Oklahoma Ouachita Mountains. In: Nodvin, S.C., Waldrop, T.A. (Eds.), Proceedings of the International Symposium on Fire, the Environment: Ecological, Cultural, Perspectives, 20–24 March, 1990, USDA For. Serv. Gen. Tech Re SE-GTR-69, pp. 168–176.

Masters, R.E., Engle, D.M., Robinson, R., 1993. Effects of timber harvest and periodic fire on soil chemical properties in the Ouachita Mountains. South J. Appl. For. 17, 139–145.

Masters, R.E., Skeen, J.E., Whitehead, J., 1995. Preliminary fire history of McCurtain County Wilderness Area and implications for red-cockaded woodpecker management. In: Kulhavy, D.L., Hooper, R.G., Costa, R. (Eds.), Red-Cockaded Woodpecker: Species Recovery, Ecology, and Management. Center Of Applied Studies, Stephen F. Austin University, Nacogdoches, TX, pp. 290–302.

Masters, R.E., Wilson, C.W., Bukenhofer, G.A., Payton, M.E., 1996. Effects of pine-grassland restoration for red-cockaded woodpeckers on white-tailed deer forage production. Wildife Soc. Bull. 24, 77–84.

McKee, W.H., Jr., 1982. Changes in soil fertility following prescribed burning on coastal pine sites. USDA For. Serv. Res. Pa SE-RP-234.

McKee, W.H., Jr., 1991. Long-term impacts of fire on coastal plain pine soils. In. Nodvin, S.C., Waldrop, T.A. (Eds.), Proceedings of the International Symposium on Fire and the Environment: Ecological and Cultural Perspectives, 20–24 March 1990. USDA For. Serv. Gen. Tech Re SE-GTR-69, pp. 405–413.

Mehlich, A., 1984. Mehlich 3 soil extractant: a modification of Mehlich 2 extractant. Comm. Soil Sci. Plant Anal. 15, 1409–1416.

Moehring, D.M, Grano, C.X., Basset, J.R., 1966. Properties of forest loess soils after repeated prescribed burns. USDA For. Serv. Res. Note SO-RN-40.

Monleon, V.J., Cromack Jr., K., Landsberg, J.D., 1997. Short- and long-term effects of prescribed underburning on nitrogen availability in ponderosa pine stands in central Oregon. Can. J. For. Res. 27, 369–378.

Morris, S.J., Boerner, R.E.J., 1998. Interactive influences of silvicultural management and soil chemistry upon soil microbial abundance and nitrogen mineralization. For. Ecol. Manage. 103, 129–193.

Mugasha, A.G., Pluth, D.J., Higginbotham, K.O., Takyi, S.K., 1991. Foliar responses of black spruce to thinning and fertilization on a drained shallow peat. Can. J. For. Res. 21, 152–163.

Ngono, G., Fisher, R.F., 2001. Predicting response of Southeast Texas loblolly pine to fertilization. South J. Appl. For. 25 (2), 84–87.

NRCS, 1998. Soil survey of Scott County. United States Department of Agriculture, Natural Resource Conversation Service.

Nuttall, T., 1981. Lottinville, S. (Ed.), A journal of travels into the Arkansas Territory during the year of 1819, 1980. University of Oklahoma Press, Norman, OK.

Pang, P.C., Barclay, H.J., McCullough, K., 1987. Aboveground nutrient distributions within trees and stands in thinned and fertilized Douglas-fir. Can. J. For. Res. 17, 1379–1384.

Powers, R.F., 1980. Mineralizable soil nitrogen as an index of nitrogen availability to forest trees. Soil Sci. Soc. Am. J. 44, 1314–1320.

Schoch, P., Binkley, D., 1986. Prescribed burning increases nitrogen availability in a mature loblolly pine stand. For. Ecol. Manage. 14, 13–22.

Schultz, R.P., 1997. Loblolly pine: The ecology and culture of loblolly pine (*Pinus taeda* L.). USDA Agric. Handbook 713.

Seifert, J.C., Liechty, H.O., Spetich, M.A., Marion, D.A., 2004. Volume, mass, and nutrients of down woody debris following initial shortleaf pine-bluestem grass restoration activities in the Ouachita Mountains of Arkansas. In: Connor, K. (Ed.), Proceedings of the 12th Biennial Southern Silviculture Research Conference, 24–28 February 2003, Biloxi, Ms. USDA For. Serv. SRS-GTR 70, pp. 115–118.

Seifert, J.C., 2004. Effects of initial pine-bluestem restoration activities and landscape characteristics on coarse and fine woody debris in two watersheds in the Ouachita National Forest. MS Thesis. School of Forest Resources, University of Arkansas at Monticello, pp. 136.

Shelton, M.G., Murphy, P.A., 1991. Age and size structure of a shortleaf pine-oak stand in Ouachita Mountains—implications for uneven-aged management. In: Coleman, S.S., Neary, D.G. (Eds.), Proceedings of the Sixth Biennial Southern Silviculture Research Conference, 30 October–1 November 1990, Memphis, TN. USDA For. Serv. SE-GTR 70, pp. 616–629.

Smith, K.L., 1986. Sawmill. University of Arkansas Press, Fayetteville, AR, 246.

Sparks, J.C., Masters, R.E., Engle, D.M., Palmer, M.W., Bukenhofer, G.A., 1998. Effects of late growing-season and late dormant-season prescribed fire on herbaceous vegetation in restored pine-grassland communities. J. Veg. Sci. 9, 133–142.

USDA Forest Service, 1996. Renewal of the shortleaf pine/bluestem grass ecosystem and recovery of the red-cockaded woodpecker: final environmental impact statement for an amendment to the land and resource management plan. USDA For. Serv. Ouachita Nat. For., Hot Springs, AR, pp. 94.

Vance, E.D., Henderson, G.S., 1984. Soil nitrogen availability following long-term burning in an oak-hickory forest. Soil Sci. Am. J. 48, 184–190.

Velazquez-Martinez, A., Perry, D.A., Bell, T.E., 1992. Response of aboveground biomass increment, growth efficiency, and foliar nutrients to thinning, fertilization, and pruning in young Douglas-fir plantations in the central Oregon Cascades. Can. J. For. Res. 22, 1278–1289.

Waldrop, T.A., Van Lear, D.H., Lloyd, F.T., Harms, W.R., 1987. Long-term studies of prescribed burning in loblolly pine forests of the Southeastern Coastal Plain. USDA For. Serv. Gen. Tech. Re SE-GTR-45.

Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid tritration method. Soil Sci. 37, 29–38.

White, C.S., 1986. Effects of prescribed fire on rates of decomposition and nitrogen mineralization in a ponderosa pine ecosystem. Biol. Fertil. Soils 2, 87–95.

Wright, R.J., Hart, S.C., 1997. Nitrogen and phosphorus status in a ponderosa pine forest after 20 years of interval burning. Ecoscience 4, 526–533.