Impacts of Shortleaf Pine-Hardwood Forest Management on Soils in the Ouachita Highlands: A Review

Hal O. Liechty, *School of Forest Resources, University of Arkansas Monticello, P.O. Box 3468, Monticello, AR 71656;* **Michael G. Shelton,** *USDA Forest Service, Southern Research Station, P.O. Box 3516, Monticello, AR 71656;* **Kenneth R. Luckow,** *USDA Forest Service, Ouachita National Forest, P.O. Box 1270, Hot Springs, AR 71902;* **Donald J. Turton,** *Department of Forestry, Oklahoma State University, Room 008c, Agric. Hall, Stillwater, OK 74078-0491.*

ABSTRACT: *Shortleaf pine (*Pinus echinata *Mill.) is the most ecologically and economically important tree species in the Ouachita Highlands of the southcentral United States. This species can occur in relatively pure stands but most frequently exists in mixed stands with various hardwood species. Because of the diversity of land ownership, public concerns about forest management, and increased intensity of forest practices, the Ouachita Highlands have been a focal point for numerous research projects over the past 20 yr that have studied how forest management affects soils. We summarized information in four fundamental areas: (1) compaction, (2) soil loss, (3) organic matter, and (4) nutrients to better evaluate if and to what degree management practices such as harvesting and prescribed fire modify the productivity and sustainability of soils in this region. The review indicated that soils with less than 15% rock content or sandy loam textures were susceptible to compaction when harvested during wet weather conditions. Although partial harvesting techniques, such as single-tree or group selection, tended to reduce overall soil disturbance in a stand, it increased soil compaction on primary skid trails by concentrating traffic on fewer skid trails. Compaction on skid trails frequently elevated bulk density to levels that could reduce regeneration success or seedling growth. Using current harvesting systems, soil losses and displacement to streams after harvesting appeared to have little or no effect on long-term soil productivity. Harvesting and prescribed fires significantly altered nutrient and organic matter contents of the forest floor and mineral soil. However, recovery of these nutrient or organic pools often occurred rapidly after these cultural practices occurred. Little information was available for determining how repeated silvicultural practices over multiple rotations would affect long-term soil productivity in the Ouachita Highlands. South. J. Appl. For. 26(1):43–51.*

Key Words: Sustainable management, soil productivity, soil compaction, forest floor, nutrients.

The Ouachita Highlands occupy approximately 2.3 million ha (Bailey 1995) in west-central Arkansas and southeastern Oklahoma and are bordered by prairie to the west, the Gulf Coastal Plain to the south, the Lower Mississippi Alluvial Floodplain to the east, and the Ozark Mountains and Arkansas River Valley to the north. Three subdivisions occur within the Ouachita Highlands: the Central Ouachita Mountains, the Fourche Mountains, and at the northern edge, the Arkansas Valley and Ridges. Elevation in the mountain systems ranges between 150 to 850 m above sea level. Soil type and composition differs by topography, aspect, and parent material within the landscape. Soils occurring on upper slopes and south-facing aspects tend to be shallower and contain more rock fragments than in other slope positions or aspects.

Soils in this region support a wide variety of forest types and communities. Generally the most economically and ecologically important forests in this region contain a significant amount of shortleaf pine (*Pinus echinata* Mill.). Although almost pure stands of shortleaf pine occur, hardwood species such as red maple (*Acer rubrum* L.), sweetgum (*Liquidambar styraciflua* L.), black gum (*Nyssa sylvatica* Marsh.), white oak (*Quercus alba* L.), northern red oak (*Q. rubra* L.), southern red oak (*Q. falcata* Michx.), post oak (*Q. stellata* Wang.), black oak (*Q. velutina* Lam.), and flowering dogwood (*Cornus florida* L.) frequently occur in various mixtures with shortleaf pine. In the southern portion of the mountain range and at lower elevations, loblolly pine (*P. taeda* L.) also naturally occurs with shortleaf pine (Guldin 1986, Schultz 1997).

NOTE: Hal O. Liechty can be reached at (870)460-1452; Fax: (870)460-1092; E-mail: Liechty@uamont.edu. Manuscript received September 12, 2000, accepted February 9, 2001.

The shortleaf pine resource in the Ouachita Highlands is of national as well as regional significance. Shortleaf pine contributes approximately one-quarter of the total southern pine volume in the United States (Murphy and Farrar 1985). Within the United States there are approximately 3.8 million ha in the shortleaf pine forest type of which approximately 29% occurs in Arkansas and Oklahoma (McWilliams et al. 1986). The Ouachita Highlands contain the majority of the shortleaf pine growing stock volume in Arkansas and Oklahoma (Miller et al. 1993, London 1997, Rosson and London 1997). We estimate that between 80 and 90 million m^3 of shortleaf pine growing stock currently exists in the Ouachita Highlands (Franco et al. 1993, Rosson and London 1997). This volume represents approximately 50% of the total growing stock in the Ouachita Highlands. Considering the dominance of the shortleaf pine forests in the Ouachita Highlands and the economic importance of this forest type, sustainable management of the resource is valued by society on a local, regional, and national scale.

Intensive management of loblolly and shortleaf pine also occurs within the Ouachita Highlands. Franco et al. (1993) indicate that approximately 44% of the pine forest type in southeastern Oklahoma is planted loblolly or shortleaf pine. Management of these forests includes the use of herbicide, fertilizer, mechanical site preparation, and clearcutting.

Ownership of the shortleaf pine resource in the Ouachita Highlands is diverse. Nonindustrial private landowners, industrial private entities, and public agencies each own approximately one-third of the land capable of supporting shortleaf pine (Franco et al. 1993, Rosson and London 1997). This diversity of land ownership, in addition to the diversity of individuals who utilize these resources, has intensified the need to manage forest resources sustainably. These interests have frequently led to cooperative as well as individual research efforts by public and private industrial landowners to determine the effect of forest management on soil and water resources. The intent of this article is to summarize findings from research on the effects of forest management on soil quality and sustainability conducted within shortleaf pine–hardwood in the Ouachita Highlands. Research within this region has generally focused on effects of various harvesting intensities, regeneration techniques, and intermediate silvicultural practices on soil resources. Thus, we will also focus on these areas of information. Finally, we will make recommendations concerning additional research needs associated with forest management and soils in this unique region.

Soils and Productivity

Shortleaf pine occupies a wide range of topography and soils in the Ouachita Highlands (Guldin 1986). Productivity increases with soil depth and is maximized on well-drained, deep, medium-textured soils (Graney 1986, Guldin 1986). In well-drained Upper Coastal Plain soils at the base of the Ouachita Mountains, site index (base age 50) is as high as 30 m, but in shallow soils on upper slopes, site index is as low as 9 m (Graney 1986). In these deep soils on the southern border of the Ouachita Highlands, loblolly pine is a major stand component on sites that can support shortleaf pine. However, at higher elevations and latitudes, loblolly pine decreases in importance and shortleaf pine dominates (Guldin 1986). Over 100 soil mapping units have been delineated in the Ouachita Highlands. Shortleaf pine occurs most frequently on soils classified as Typic Hapludults but also occurs on Typic Paleudults, Typic or Lithic Dystrochrepts, Typic Udifluents, Typic Fragiudults, Aquic or Lithic Hapludults, Typic Fragiudalfs, and Typic Paleudalfs (Luckow unpublished data). These soils are typically moderately deep to deep (50–150 cm), with shortleaf pine site indices (base age 50) between 18 and 21 m. In soils with depths less than 50 cm, site indices are typically between 12 and 15 m (Luckow unpublished data).

The most serious impact of forest management on the deep soils located on flat or low grade terrains within the Ouachita Highlands is the compaction of seasonally wet soils (USDA Forest Service 1990). On more shallow soils located on steeper slopes, potential deleterious impacts of forest management include moderate to severe soil erosion (USDA Forest Service 1990). Although there is no available estimate of what proportion of the Ouachita Highlands have the potential for moderate or high levels of erosion, about 27% of the Ouachita National Forest, or approximately one-third of the Ouachita Highlands, has slopes of more than 35%.

Soil Compaction

A number of studies conducted in the Ouachita Mountains have shown that susceptibility to compaction is strongly related to soil characteristics, soil moisture levels, and type of harvesting activity. Luckow (1998) studied 20 stands and found that bulk density increased within the surface 20 cm of mineral soil after only one or two passes by a skidder. Compaction was generally greater in soils containing less than 15% rocks by volume compared to soils containing more than 15% rocks by volume (Table 1). After only one or two skidder passes, average bulk densities of soils with less than 15% rock content increased from 1.32 g/cm^3 to 1.41 g/cm^3 while soils with more than 15% rock content increased from 1.32 to 1.38 g/cm^3. On primary skid trails, soils with less than 15% rock content had bulk densities that were approximately 8% greater than soils with more than 15% rock content. Soils on sites harvested during the wet season (December–June) were compacted to a greater degree than similar soils on sites harvested during the dry season (July–November). Bulk density of soils in primary and secondary skid trails selected from sites containing less than 15% rock were, respectively, 14 and 11% greater than undisturbed soils when harvested during the dry season but 21 and 14% greater than undisturbed soils when harvested during the wet season (Table 1). Luckow (1998) also found that wet-season harvesting tended to exacerbate compaction of sandy loam soils to a higher degree than loam or silt loam soils. These effects were not short-lived. Luckow (1998) observed elevated bulk densities in soils that appear to have been disturbed at least 20 yr prior to the study. Results from this study were consistent with studies from the same or other regions investigating the influence of rocks (Cullen et al. 1991, Turton et al. 1997), soil

Table 1. Bulk density within the surface 20 cm of mineral soil for six levels of disturbance in stands containing soils with either less than 15% or more than 15% rock content by volume, harvested in either the wet (December–June) or dry (July–November) season, and soils with either sandy loam or loam to silt loam textures in the Ouachita Mountains (Luckow 1998).*

	Level of disturbance					
	Undisturbed	1–2 passes	Secondary skid trail	Primary skid trail	Landing/road	Old disturbance
Rock content	[All seasons and textures (g/cm³)]					
≤15%	1.32a†	1.41a	1.49a	1.57a	1.61a	1.44a
>15%	1.32a	1.38b	1.43b	1.45b	1.57a	1.42a
Season	[Soils with ≤15% rock content (g/cm³)]					
Dry	1.32a	1.38b	1.47b	1.51b	1.55b	NA
Wet	1.33a	1.43a	1.50a	1.60a	1.67a	NA
Season	[Soils with >15% rock content (g/cm³)]					
Dry	1.31a	1.37a	1.42a	1.44a	1.49a	NA
Wet	1.32a	1.39a	1.44a	1.46a	1.61a	NA
Soil texture	[Soils with ≤15% rock content (g/cm³)]					
Sandy loam	1.35a	1.46a	1.51a	1.64a	1.72a	1.45a
Loam/silt loam	1.31a	1.38b	1.48a	1.54b	1.56b	1.44a

* Bulk density measurements were taken on approximately 75 points from randomly located transects within 2 5 ac subplots in 20 stands harvested no more than 1 yr prior to the study. A Troxler™ 3440 moisture/density gauge was used for determining bulk density and readings were adjusted by rock content to give values on a rock-free basis.

† Means from a specific disturbance level and comparison followed by the same letter are not significantly different ($\alpha = 0.05$).

moisture (Switzer et al. 1978, Guo 1989; Guo and Karr 1989, Rachal and Karr 1989, Preston 1997), and soil particle size (Lull 1959) on compaction. These results suggest that soil texture and rock content can be used to delineate sites that are at risk of soil compaction.

Kluender et al. (1994) and Stokes et al. (1995) have reported that the type of regeneration harvesting method determines area of soil disturbance and compaction in shortleaf pine–hardwood stands in the Ouachita Mountains. Kluender et al. (1994) found that clearcuts and shelterwoods had less area untrafficked (17.3 and 10.5%, respectively) than stands harvested with single-tree selection (42.4%). The proportion of the area disturbed by primary and secondary skid trails was also greater in clearcuts (15.0%) and shelterwoods (16.7%) than in stands selectively harvested (6.9%) (Kluender et al. 1994). Stokes et al. (1995) found that the percentage of area in primary or secondary skid trails within harvested shortleaf pine–hardwood stands was respectively 14.3, 14.6, 22.6, 19.8, and 22.4% for single-tree selection, group selection, shelterwood, seed-tree harvests, and clearcuts. Average areas in primary and secondary skid trails reported by Luckow (1998) averaged 38.5% of the total harvested areas, but harvesting methods were not reported. All three studies indicated a general but weak positive correlation between disturbance area and harvesting intensity.

The studies by Stokes et al. (1993) and Stokes et al. (1995) indicate that the number of trees or basal area of trees removed affects the amount of disturbance area in a site. For example, the untrafficked portion of stands harvested using single-tree selection, shelterwoods, and clearcutting methods was reported to be respectively 39.4 to 42.4, 13.1 to 17.3, and 6.6 to 10.5% while the proportion of the merchantable trees removed from the stand by each of these three harvesting methods was respectively 37 to 40, 64 to 73, and 100% (Stokes et al. 1993, Stokes et al. 1995). As a greater proportion of the stand was removed, trafficking occurred on a greater proportion of the stand area. However, there was not a linear increase in disturbance with tree removal. For example, an average of 59% of the stand area was disturbed to remove 39% of the merchantable trees using the single-tree selection but only an additional 26% of the stand was disturbed to remove an additional 29% of the stand using a shelterwood harvest. To remove an additional 32% of the stand using clearcutting only required an additional 6% of stand to be disturbed. To what degree the differences in disturbance to tree removal ratios reflect differences in harvesting methods or whether these changes in ratios reflect an ever-decreasing amount of untrafficked stand area is not known.

The level of soil compaction is also affected by harvesting methods. Kluender et al. (1994) and Stokes et al. (1993) reported that the bulk density of the surface 10 cm in primary skid trails after single-tree selection harvests (1.49 g/cm^3) was significantly greater than the soil bulk density in undisturbed areas (1.12 g/cm^3). Differences in bulk density between skid trails and undisturbed areas were not significant after shelterwood harvests (1.30 compared to 1.22 g/cm^3) or clearcuts (1.26 compared to 1.15 g/cm^3). Turton et al. (1997) found that rock-free bulk density was significantly greater in than out of skidder tracks within the surface 10 cm of soil in stands harvested using group selection (1.14 vs. 1.00 g/cm^3) or single-tree selection (1.24 vs. 1.07 g/cm^3) and from a depth of 10 to 20 cm in stands using the single-tree selection only (1.44 vs. 1.25 g/cm^3). Samples taken in and outside of tracks within shelterwoods or clearcuts did not significantly differ. Turton et al. (1997) and Kluender et al. (1994) concluded that selection harvesting methods generally concentrated travel by wheeled vehicles to a smaller area of skid trails thereby increasing the level of compaction in the primary and secondary skid trails. Harvesting methods such as clearcuts or shelterwoods decreased the number of passes and thus compaction in individual skid trails. However, as indicated previously, the overall disturbance is more dispersed and occurs over a greater area using clearcut or shelterwood harvesting systems.

Little is known concerning the effects of compaction and soil bulk density on growth, survival, or health of shortleaf pine. Even for species that have been thoroughly studied, limitations of increased bulk density on growth and survival are difficult to determine without specific soil, site, and climatic information. To give an estimate how alteration of soil bulk density could affect survival of regeneration in the Ouachita Highlands, we used results from a study investigating establishment success of loblolly pine on eroded sites (Duffy and McClurkin 1974). This study indicated that surface soil bulk densities of greater than 1.45 g/cm^3 could retard regeneration success. Using this bulk density as an upper limit and results of Kluender et al. (1994), we evaluated the potential effects of different harvesting methods on shortleaf pine regeneration. This comparison indicated that regeneration failures could occur in primary skid trails if stands were harvested using single-tree selection, but not shelterwoods or clearcuts. Given the amount of land disturbed by primary trails, one could expect regeneration failures on approximately 4.3% of the stand harvested by single-tree selection. Using Luckow's (1998) data and these same criteria, regeneration failures could also occur on primary skid trails, secondary skid trails, and landings within stands harvested during wet weather and soils containing less than 15% rock content by volume (Table 1). These disturbances represented up to 42% of the total area of these stands. We recognize that increases in bulk density could alter survival of shortleaf pine differently than loblolly pine. Shortleaf pine has been reported to have a larger root system (Zak 1961) but a lower tolerance to poor soil aeration (Lawson 1990) than loblolly pine. Without further information concerning the relationship between soil bulk density and shortleaf pine seedling survival, it is not possible to more accurately predict how these changes in bulk density affect shortleaf pine regeneration.

Increases in soil bulk density can not only reduce survival of pine seedlings but also growth of seedlings and mature trees. Reductions in aboveground height or volume growth are often associated with increases in bulk density (Froehlich and McNabb 1984) and may reflect reductions in root growth (Fisher and Binkley 2000). In response to these concerns, soil quality standards for several administrative National Forest Service Regions require that forest management activities do not increase bulk density more than 15% (Powers and Avers 1992). This compaction limit was only exceeded in primary skid trails observed by Kluender et al. (1994) and Stokes et al. (1993) after single-tree selection harvesting and landings or in some instances primary skid trails studied by Luckow (1998).

Soil Loss

Forest management on steep, erodable soils can exacerbate soil erosion and loss. Several small watershed studies were established in the Ouachita Mountains to evaluate the impacts of forest harvesting on water quality and can be used to quantify soil loss from harvesting activities (Table 2). The experimental watersheds were generally 0.5 to 6 ha in size, had average slopes of 13–17%, and were drained by ephemeral streams. Slopes up to 30% were common. Harvesting treatments included clearcutting, single-tree selection, and shelterwoods. Soil loss was the greatest during the first year after harvesting in watersheds that were clearcut (Table 2). Losses were generally low, less than predicted by the Universal Soil Loss Equation for clearcutting in the Ouachita Mountains, and less or similar to sediment loss observed in Upper Gulf Coastal Plain (Scoles et al. 1994). Generally, elevated

Table 2. Annual sediment yields in several watershed studies in the Ouachita Mountains

Watersheds and treatments	Pretreatment average	Years after treatment 1	2	3	4
	[Average annual sediment yield (kg/ha)]				
Alum Creek watersheds 1–3 (Rogerson 1985)					
CC, MS, H*	18.3	130.9	7.1	14.2	
SW,H,MS	9.8	35.1	5.7	12.6	
UC	10.9	10.5	6.1	7.0	
Athens Plateau watersheds 1–9 (Beasley et al. 1986)					
CC,RS,S,W,P	62a†	535b	1,005a	308a	
CC,RS,H,P	44a	251a	205a	90a	
UC	32a	71a	147a	46a	
Ouachita Mtn., OK watersheds 1–6 (Miller 1984)					
CC,RS,H,B,R,P		282b	35b	15b	43a
UC		36a	8a	5a	24a
Ouachita Mtn., AR watersheds 10–18 (Miller et al. 1988)					
CC,RS,DC,B,P		237a	90a	177a	
STS,RS		26b	36a	84a	
UC		12b	15a	68a	

* Treatments: CC = clearcut, SW = shelterwood, UC = uncut, STS = single tree selection, S = sheared, MS = mule skidded, RS = rubber tired skidded, C = chopped, W = windrowed, DC = drum roller chopped, H = herbicides, B = burn, R = ripped, P = planted with pine.

† Sediment yields for a given year and study with the same letter are not significantly different ($\alpha = 0.05$).

rates of soil loss only occurred during the first 1 or 2 yr after harvesting. Partial cuttings, such as single-tree selection and shelterwoods, did not produce a significant increase in sediment loss. Low levels of soil loss were attributed to high gravel/rock content of the soils (Scoles et al. 1994), rapid revegetation of the site (Beasley and Granillo 1985, Scoles et al. 1994), woody debris remaining after harvesting (Beasley et al. 1986, Scoles et al. 1994), fine roots remaining in the surface soil after harvesting (Miller et al. 1985, Wheeler and Eichman 1991), and contour ripping which retains sediments (Miller 1984, Miller et al. 1985, Scoles et al. 1994). Beasley et al. (1986) found that mechanical site preparation techniques generally increased soil loss over levels found with other site preparation techniques. Clearcutting followed by mechanical site preparation increased soil loss above those found when clearcutting was followed by only chemical control of competing vegetation (Table 2). Sediment loss was still higher in the watersheds mechanically site prepared than in uncut watersheds 3 yr after treatment, but differences were not statistically significant.

Assuming a worse-case scenario, we used the increased level of sediment loss after clearcutting followed by shearing and windrowing observed by Beasley et al. (1986) to estimate the potential reductions in soil depth from these activities. If soil loss was uniform across the site, bulk density equaled 1.1 g/cm^3, and by the fourth year after harvesting sediment losses returned to preharvest levels, the sediment loss observed by Beasley et al. 1986 would represent a removal of 0.14 mm of soil. This loss of soil should have a negligible effect on tree and community productivity over normal rotation lengths of 40–60 yr. If soil losses were concentrated in a portion of rather than uniformly distributed over the harvested area, tree and soil productivity could be reduced in the areas of concentrated soil loss. The use of chemical rather than mechanical site preparation and partial cuttings rather than clearcutting will obviously reduce the risk of soil loss. However, given the relatively low level of soil loss and risks to soil productivity associated with mechanical site preparation and clearcutting, alternative management techniques are probably more beneficial for reducing sediment inputs to streams and maintaining water quality than for maintaining soil productivity.

Organic Matter

Forest management activities, such as harvesting and prescribed burning, have the potential to alter inputs of organic matter to the soil surface and thus the organic matter content of soils. Timber removal reduces annual litterfall for several years after harvesting, but supplies a one-time input of woody material to the site in the form of logging slash (Kimmins 1997). Studies in the Ouachita Mountains by Liechty and Shelton (1998, in press) suggest that tree removal does not significantly alter the total amount of organic matter in fine and nonwoody forest floor components but drastically increases the amount of coarse woody debris. They found that total organic matter in fine woody and nonwoody forest floor components within clearcuts, shelterwoods, and stands harvested using single-tree selection were not significantly different than in uncut stands 3 yr after harvesting (Table 3). They attributed the lack of any change in organic matter in the clearcuts and shelterwood cuts to the prolific increase in herbaceous and shrub vegetation after harvesting. Litter inputs from this understory vegetation offset the losses of litter inputs from the overstory that was removed. If herbaceous vegetation growth was controlled, it is likely that forest floor levels in the clearcuts and shelterwoods would have been reduced below levels found in the uncut stands.

Liechty and Shelton (1998) reported that mass of coarse woody debris in the harvested stands was five to eight times greater than in uncut stands. A large portion of this material was attributed to residual slash left after harvesting and unmerchantable hardwoods felled for competition control. In areas where markets for hardwoods are available, differences in amounts of coarse woody debris would be reduced. If coarse woody debris were included in calculations of forest floor organic matter content, stands that are harvested would have higher levels of organic matter in the forest floor than the uncut stands 3 yr after harvesting. However, the forest floor of harvested stands would undoubtedly be of a different character than that in the uncut stands.

When fire is utilized in the management of shortleaf pine, the amount of forest floor is drastically reduced. Masters et al. (1993) found that clearcut plots receiving a site preparation burn contained 54% less forest floor than uncut/unburned study plots 6 yr after harvesting (Table 3). Beasley et al. (1988) also found that a 7-yr-old plantation, which was broadcast-burned and roller-chopped, had 36% less forest floor than an adjacent uncut stand (Table 3). Greater reductions in forest floor were realized in study sites that were repeatedly burned over a number of years (Masters et al. 1993). Study sites that were thinned to a residual basal area of 9 m^2/ha and annually burned for 6 yr contained only 1.6% of the forest floor found in the uncut/unburned plots and 3.5% of the forest floor found in the previously mentioned clearcut

Table 3. Forest floor mass (L+F layers) for several harvesting methods and burning regimes in the Ouachita Mountains

	Years after treatment		
Study and treatments	3	6	7
	[Forest floor mass (Mg/ha)]		
Liechty and Shelton 1998*			
CC†	15.0a††		
SW	18.1a		
STS	16.9a		
UC	17.8a		
Masters et al. 1993			
CC, SPB, P	1.8cd	4.0bc	
PH, HT, 1YB	0.6cd	0.1e	
PH, HT, 2YB	1.6cd	2.0cd	
PH, HT, 4YB	4.8ab	2.5b	
UC	6.0a	8.0a	
Beasley et al. 1988			
CC, DC, SPB, P			9.8
UC			15.2

* Values of Liechty and Shelton (1998) were corrected for ash content.

† Treatments: CC = clearcut, SW = shelterwood, UC = uncut, PH = Merchantable pine harvested, HT = Hardwoods thinned to 40 ft^2/ac, SPB = Site preparation burn, DC = Drum roller chopped, P = Planted to pines, STS = Single Tree Selection, 1YB = Annual burn, 2YB = 2 yr burn interval, 4YB = 4 yr burn interval.

†† Mass for a given year and study with the same letter are not significantly different (α = 0.05).

plots (Table 3). As the interval between fires increased, amounts of forest floor also increased. The proportional reductions in forest floor by biennial burning and burning on a 4 yr interval were similar to reductions found on long-term annually and/or biennially burned sites in the Atlantic and Gulf Coastal Plains (McKee 1982, Binkley 1986). However, reductions in forest floor observed by Masters et al. (1993) with annual burns (90%) were generally greater than those observed with annual burning (44-84%) in the Atlantic and Gulf Coastal Plains (McKee 1982).

Although it is evident that forest management can alter the amounts of organic matter in the forest floor, the effect of forest management on mineral soil organic matter in shortleaf pine–hardwood communities is not as clear. Three years after clearcutting, only the surface 2.5 cm of soil (O_a and mineral soil) remained altered by harvesting (Liechty and Shelton 1998). Loss-on-ignition was reduced from 19.5 to 14.4%, but no significant changes in loss-on-ignition were found in the two other depths (2.5–15 cm and 15–30 cm) or at any depth in stands harvested using single-tree selection or shelterwood methods. Stoin et al. (1985) found that organic matter concentrations in the surface 6 cm of mineral soil were reduced immediately after a site preparation burn that followed clearcutting and roller chopping of three watersheds in the Ouachita Mountains (Figure 1). By the end of the summer the year following clearcutting, organic matter concentrations in these clearcut watersheds were greater than in three uncut watersheds. Concentrations then decreased during the second year and by the end of the second summer were similar to concentrations in the uncut watersheds. Stoin et al. (1985) attributed initial decreases in organic matter to combustion by the fire and increased decomposition associated with soil disturbance. The rapid increase following this period was related to the proliferation of new roots in the mineral soil as the watersheds were revegetated (Stoin et al. 1985). Recovery of these soils was extremely rapid indicating mineral soil organic matter contents should not be permanently or significantly reduced under normal harvesting intensities. Luckow (unpublished data) found higher levels of soil organic matter in the surface 15 cm of mineral soil in three stands that had been thinned and frequently burned during the last 20 yr than in stands that had not been thinned and burned. However, differences were not statistically significant. Results from the Atlantic and Gulf Coastal Plains have also indicated statistically insignificant increases in soil organic matter after prolonged burning (McKee 1982, 1991).

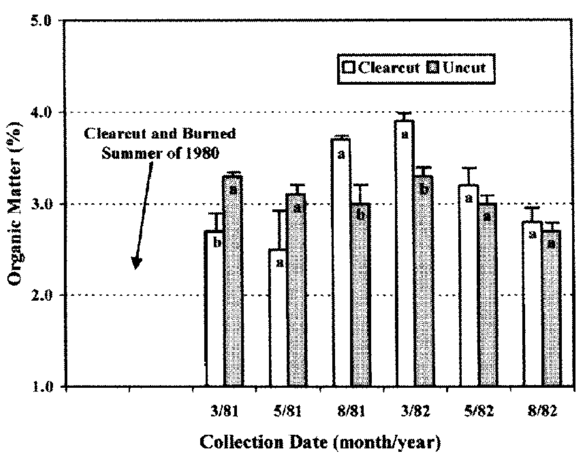

Figure 1. Mean and standard deviation for organic matter concentrations in surface 6 cm of mineral soil from three clearcut watersheds and three uncut watersheds in the Ouachita Mountains for 2 yr after harvesting and site preparation (Stoin et al. 1985). Bars with same letter for a given collection date are not significantly different ($\alpha = 0.10$).

Nutrient Regimes and Availability

The maintenance of nutrient levels for adequate tree growth has long been recognized as an important component in soil sustainability. Removal of forest products and alteration of nutrient cycling can increase site nutrient losses through biomass removal, increased leaching, and alteration of carbon inputs to soils (Silkworth and Grigal 1982, Johnson et al. 1988, Kimmins 1997, Yanai 1998, Fisher and Binkley 2000). Harvesting and associated silvicultural practices have been reported to both decrease (Knoepp and Swank 1997) and increase (Hix and Barnes 1984, Hendrickson et al. 1989) soil nutrient pools.

A number of studies in the Ouachita Highlands have evaluated relatively short-term changes in nutrient status after harvesting by comparing harvested and uncut stands. For example, Liechty and Shelton (in press) found that several types of forest harvesting methods significantly altered fine and nonwoody forest floor concentrations and pools of N, P, Mg, S, or Mn. Three years after harvesting, concentrations of N, P, Mg, S, and Mn were respectively reduced as much as 21, 16, 21, 21, and 70% (Liechty and Shelton, in press). Reductions in concentrations were related to the alteration of forest floor composition (proportion of herbaceous, pine, hardwood, and woody materials) associated with pine removal and herbaceous vegetation proliferation, postharvest decreases in nutrient concentrations of hardwood and pine foliage litter, and mixing of mineral soil with forest floor. Changes in concentrations of nutrients, such as Mg and Mn, were most pronounced in partial cuttings that removed rather than retained hardwoods. Concentrations of Mg and Mn in hardwood foliage are 40–50% greater than in pine foliage, and thus reductions in the amount of hardwood foliage in the forest floor reduced concentrations of these elements. Liechty and Shelton (1998) concluded that changes in the forest floor would not have any short-term effect on the nutrient status of the soils due to the addition of nutrients contained in coarse woody debris. The additional nutrients added by the logging slash more than compensated for any losses or changes in nutrient pools observed in the fine and non-woody forest floor.

Short-term changes in mineral soil nutrient status also appear to be minimal after harvesting. Soil nutrient concentrations at three depths in 20 shortleaf pine-hardwood stands prior to and 3 yr after harvesting did not differ (Liechty and Shelton 1998). Stoin et al. (1985) found that soil NH_4-N, NO_3-N, and available P increased rapidly during the first 18 months after clearcutting and a site preparation fire. Concentrations of available P in the clearcut watersheds were approximately 200% greater than concentrations in the uncut watersheds. Concentrations of NH_4-N, and NO_3-N were respectively 26 and 73% greater in the clearcut watersheds than in the uncut watersheds over this same period of time. Although concentrations decreased over time, NO_3-N and available P levels were significantly elevated above uncut watersheds up to 2 yr after harvesting. Stoin et al. (1985) attributed increased concentrations in the clearcut watersheds to high decomposition and mineralization rates immediately after harvesting. The ensuing reduction in concentrations was a result of the rapid revegetation of the watersheds and associated uptake of the nutrients by the plants. At no time did concentrations in the clearcuts fall below uncut levels. Both of these studies indicate that reductions of soil nutrients within shortleaf pine-hardwood stands do not generally occur under current harvesting strategies.

Masters et al. (1993) concluded that fires following harvesting increase soil concentrations of K, Ca, and Mg. Four and one-half years after initiation of the study, Masters et al. (1993) observed the greatest increases in a thinned stand that had been burned initially after a thinning and every 3 yr thereafter. Burning regimes implemented for longer periods of time appear to alter soil nutrient regimes to a greater degree. Luckow (unpublished data) found that three shortleaf pine stands that had been burned every 3 to 4 yr and periodically thinned during the past 20 yr had significantly higher concentrations of Ca and mineralizable N in the top 15 cm of soil than three stands that had not been burned or thinned. Concentration of Ca and mineralizable N were respectively 60.5 and 17.9% higher in the burned stands than unburned stands. Base saturation, cation exchange capacity, and pH were also significantly elevated in the burned stands. Elevated levels of N (McKee 1982), K, and Ca (McKee 1982, Jorgensen and Wells 1986) in soils have been reported shortly after prescribed fire or for several years after prescribed fires when burning regimes have been implemented over long periods. Binkley (1986) reported increased pH but decreased CEC in surface mineral soils after 16 yr of biennial prescribed fires in a longleaf pine stand. Studies in the Ouachita Highlands generally agree with studies in pine stands from other regions that prescribed burning generally does not decrease nutrient contents or availability in mineral soils.

Although these studies show that any short-term reductions in soil nutrient pools and concentrations from forest harvesting are minimal, they are not able to indicate the potential long-term implication of harvesting and tree removal in these communities. To better evaluate the long-term effects of harvesting on nutrient status, we used a nutrient budget approach (Table 4). We compared the amount of nutrients removed from a site in a stem-only harvest to the amounts added from atmosphere, nutrients exported by streams due to clearcutting, and nutrient reserves in the soil (Table 4). The only data available for this exercise included information for K, Ca, and Mg from a mature shortleaf pine–hardwood stand (Beasley et al.

Table 4. Estimated changes in K, Ca, and Mg pools attributed to managing a shortleaf pine-hardwood stand with a 60 yr rotation in the Ouachita Mountains.

Nutrient pools and fluxes	K	Ca	Mg
		(kg/ha)	
Site reserves prior to harvesting*			
Mineral soil (0–107cm)	1,359	2,628	881
Forest floor	7	144	11
Total reserves	1,363	2,772	892
Outputs			
Stem-only harvest*, †	139	491	60
Clearcut, stream discharge††	10	7	N/D
Total output	149	498	60
Inputs (during rotation)			
Atmospheric (wet deposition)§			
60 yr	30	103	22
Change 60 yr (output – input)	–119	–395	–38

* From Beasley et al. 1988, (K, Ca, and Mg reported as exchangeable in mineral soil, total in biomass and forest floor).
† Stem only harvest assumed to be 71% of total aboveground Ca, Mg, and K based on estimates by Johnson et al. (1990) and Wheeler and Eichman (1991).
†† Beasley et al. 1987.
§ Average annual deposition 1983–1999 National Acidic Deposition Program/National Trends Network Monitoring Location Caddo Valley (AR03), Clark County, AR.

1988). Although this stand had two age classes, we assumed a stand and rotation age of 60 yr. Exports from clearcutting reflected increased levels of nutrient discharged by watersheds in this area after clearcutting (Beasley et al. 1987). We used wet atmospheric deposition to estimate total inputs. Use of only wet deposition underestimates total inputs, which include dry atmospheric deposition as well as mineral weathering. Thus, an interpretation from this dataset is limited. For all three nutrients, outputs exceeded wet deposition inputs (Table 4). Net loss of K, Ca, and Mg over a 60 yr rotation represented respectively 9.8, 14.2, and 4.2% of total reserves. Net losses of K and Mg as a proportion of total reserves were similar to proportional losses estimated for K (3–13%) and Mg (5–10%) from six different forest types and assuming three total tree harvests during a 120 yr period (Federer et al. 1989). Our estimated proportional losses of Ca were less than those (24–74%) calculated by Federer et al. (1989). It is interesting to note that our estimates, like Federer et al. (1989), indicated that Ca has the greatest risk for potential depletion. However, considering that inputs did not include mineral weathering and dry inputs, these net losses are relatively low. Dry deposition inputs measured from locations in the Ridge and Valley Province of east Tennessee with similar latitudes and elevations to those in the Ouachita Mountains have been estimated to be between 5.5–6.2 kg/ha/yr of Ca and 0.39–0.50 kg/ha/yr of K (Johnson et al. 1985, Lindberg et al. 1989). Deposition fluxes of these magnitudes would significantly reduce the potential drain or loss of Ca and K from the mineral soil and forest floor reserves due to forest management. Inputs of theses bases from mineral weathering could be substantial given the often high amount of rock fragments greater than 2 mm in these soils. However as far as we know, weathering rates have not been estimated for this region, and thus it is difficult to quantify to what degree mineral weathering would offset any potential losses due to harvesting. Regardless of these preliminary results, in order to quantify the long-term effects of tree removal on forest nutrition, more precise estimates of pools, inputs, and outputs for a wider array of nutrients are needed for shortleaf pine communities in the Ouachita Highlands.

Conclusions

Research of the past 20 yr in the Ouachita Highlands has made a significant contribution to our understanding of the relationship between forest management and soils in this region. Studies in shortleaf pine–hardwood stands have documented increased susceptibility of soil compaction of soils with less than 15% rock content and sandy loam textures when harvested during wet weather. Harvesting in stands using single-tree or group selection methods concentrates traffic on fewer skid trails but compacts soils in skid trails to a greater degree than does other harvesting methods. Soil losses from harvesting in the Ouachita Mountains are generally low and pose little risk to reductions in soil productivity. Studies in the Ouachita Highlands have generally documented that although forest management can alter soil nutrient status and organic matter contents, these changes should not reduce soil productivity at least over short time periods (3–8 yr). In fact, the use of fire increased soil availability or contents of some macronutrients and could potentially increase productivity. It should be emphasized that these conclusions reflect only short-term (3–8 yr) results. There is little information concerning the long-term results of forest management on soils. Our estimates using a limited dataset from a mature shortleaf pine-hardwood stand indicated removals of Ca, Mg, and K from soil reserves to be between 4–14% over a 60 yr rotation.

Considering these limitations and current informational needs in the region, we recommend the following three areas for further research. First, additional information is needed concerning the effect of soil physical properties, especially bulk density, on establishment and growth of shortleaf pine stands. This information is especially critical for management of public and nonindustrial private lands in the Ouachita Highlands because natural regeneration is commonly used to regenerate stands in these ownerships. Second, much of the research during the past 20 yr has focused on quantifying changes in soil characteristics rather than soil/ecosystem processes after specific forest management practices. We recommend emphasizing research that will elucidate how, if, and to what degree forest management practices alter important soil/ecosystem processes such as decomposition, nutrient cycling, and nutrient uptake. A better understanding of these processes would enable land managers to better anticipate the long-term responses of soils to various management decisions and to more readily evaluate the implications of new practices on soil and forest sustainability. Finally, additional information is needed concerning inputs/outputs, pools, and internal movement of nutrients in shortleaf pine ecosystems. These data would allow a more precise estimate of the potential for nutrient depletion after multiple rotations in the low- to medium-quality sites that typify the Ouachita Mountains.

Literature Cited

BAILEY, R.G. 1995. Descriptions of the ecoregions of the United States. Ed. 2. USDA For. Serv. Misc. Publ. 1391. Washington, DC. 108 p.

BEASLEY, R.S., AND A.B. GRANILLO. 1985. Soil protection by natural vegetation on clearcut forestland in Arkansas. J. Soil Water Conserv. 40:379–382.

BEASLEY, R.S., A.B. GRANILLOM AND V. ZILLMER. 1986. Sediment losses from forest management: Mechanical vs. chemical site preparation after clearcutting. J. Environ. Qual. 15:413–416.

Beasley, R.S., E.L. Miller, and E.R. Lawson. 1987. Chemical properties of soils and streams in natural and disturbed forest ecosystems in the Ouachita Mountains. Arkansas Water Resour. Res. Center, Univ. Ark. Fayetteville. Tech. Completion Rep. Res. Proj. G-1212-02. 93 p.

Beasley, R.S., E.L. Miller, and E.R. Lawson, and W.R. Stogsdill. 1988. Contrasting acidic deposition and nutrient pools in an undisturbed forest and a young pine plantation in the Ouachita Mountains. Project rep.: Ark. Sci. and Tech. Authority. Proposal #86-A-0008. 41 p.

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

CULLEN, S.J., C. MONTAGNE, AND H. FERGUSON. 1991. Timber harvest trafficking and soil compaction in western Montana. Soil Sci. Am. J. Proc. 55:1416–1421.

DUFFY, P.D., AND D.C. MCCLURKIN. 1974. Difficult eroded planting sites in North Mississippi evaluated by discriminate analysis. Soil Sci. Soc. Am. J. Proc. 38:676–678.

FEDERER, C.A., J.W. HORNBECK, L.M. TRITTON, C.W. MARTIN, R.S. PIERCE, AND C.T. SMITH. 1989. Long-term depletion of calcium and other nutrients in eastern U.S. forests. Environ. Manage. 13:593–601.

FISHER, R.F., AND D. BINKLEY. 2000. Ecology and management of forest soils. Ed. 3. Wiley, New York. 489 p.

FROEHLICH, H.A., AND D.H. MCNABB. 1984. Minimizing soil compaction in Pacific Northwest forests. P. 159-192 *in* Forest soils and treatment impacts. Proc. of sixth North American forest soils conference, Stone, E.L. (ed.). Univ. Tenn., Knoxville, TN.

FRANCO, P.A, P.E. MILLER, AND A.J. HARTSELL. 1993. Forest statistics for southeast Oklahoma counties-1993. USDA For. Serv. Resour. Bull. SO-176. 31 p.

GRANEY, D.L. 1986. Site quality relationships for shortleaf pine. P. 41–52 *in* Proc. of symp. on the shortleaf pine ecosystem, Murphy, P.A. (ed.). Univ. Ark. Coop. Ext. Serv., Monticello, AR.

GULDIN, J.M. 1986. Ecology of shortleaf pine. P. 25–40 *in* Proc. of symp. on the shortleaf pine ecosystem, Murphy, P.A. (ed.). Univ. Ark. Coop. Ext. Serv., Monticello, AR.

GUO, Y. 1989. The effect of soil compaction on selected soil physical properties and loblolly pine seedling growth on Smithdale soil site in Northern Mississippi. Ph.D. Thesis, Miss. State Univ., Miss. State, MS. 130 p.

GUO, Y., AND B.L. KARR. 1989. Influence of trafficking and soil moisture on bulk density and porosity on Smithdale sandy loam in northern-central Mississippi. P. 533–538 *in* Proc. of the fifth bienn. south. silvic. res. conf., Miller, J.H. (ed.). USDA For. Serv. Gen. Tech. Rep. SO-74.

HENDRICKSON, O.Q., L. CHATARPAUL, AND D. BURGESS. 1989. Nutrient cycling following whole-tree and conventional harvest in northern mixed forest. Can. J. For. Res. 19:725–735.

HIX, D.M., AND B.V. BARNES. 1984. Effects of clear-cutting on the vegetation and soil of an eastern hemlock dominated ecosystem, western Upper Michigan. Can. J. For. Res.

JOHNSON, D.W., R.J OLSON, L.K. MANN, AND D.E. TODD. 1990. Changes in forest biomass and nutrient distribution in Walker Branch Watershed, Tennessee from 1967 to 1987. P.122–136 *in* Sustained productivity of forest soils, Gesse, S.P., et al. (eds.). Proc. of the seventh North Am. for. soils conf., Univ. of British Columbia, Fac. of For. Publ.14:914–923, Vancouver, BC.

JOHNSON, D.W., D.D. RICHTER, G.M. LOVETT, AND S.E. LINDBERG. 1985. The effects of atmospheric deposition on potassium, calcium, and magnesium cycling in two deciduous forests. Can. J. For. Res. 15:773–782.

JOHNSON, D.W., J.M. KELLY, W.T. SWANK, D.W. COLE, H. VAN MIEGROET, J.W. HORNBECK, R.S. PIERCE, AND D. VAN LEAR. 1988. The effects of leaching and whole-tree harvesting on cation budgets of several forests. J. Environ. Qual. 17:418–424.

JORGENSEN, J.R, AND C.G. WELLS. 1986. Foresters' primer in nutrient cycling. USDA For. Serv. Gen. Tech. Rep. SE-37. 42 p.

KIMMINS, J.P. 1997. Forest ecology: A foundation for sustainable management. Prentice-Hall, Englewood Cliffs, NJ. 596 p.

KLUENDER, R.A., D.A. LORTZ, AND B.J. STOKES. 1994. Production time, total costs, and residual damage at varying harvest intensities. P. 229–240 *in*

Ecosystem management research in the Ouachita Mountains: Pre-treatment conditions and preliminary findings, Baker, J.B. (ed.). USDA For. Serv. Gen. Tech. Rep. SO-112.
KNOEPP, J.D., AND W.T. SWANK. 1997. Forest management effects on surface soil carbon and nitrogen. Soil Sci. Soc. Am. J. 61: 928–935.
LAWSON, E.R. 1990. *Pinus echinata* Mill. Shortleaf pine. P. 316–326 *in* Silvics of North America: Volume 1. Conifers. Burns, R.M., and B.H. Honkala (tech. coords.). USDA For. Serv. Agric. Handb. 654.
LIECHTY, H.O., AND M.G. SHELTON. 1998. Evaluation of the effects of phase II ecosystem management reproductive cutting methods on litter/soil nutrients. USDA For. Serv. Final Rep.: Coop. Agree. FS-SO-19-92-009. 25 p.
LIECHTY, H.O., AND M.G SHELTON. In press. Changes in organic matter and nutrients in forest floor after applying several reproductive cutting methods in shortleaf pine-hardwood stands. *In* Proc. on ecosystem manage. res. in the Ouahcita and Ozark Mountains, Guldin, J.M. (comp.). USDA For. Serv. Gen. Tech. Rep. SRS-[ ].
LINDBERG, S.E., R.C. HARRISS, W.A. HOFFMAN, JR., G.M. LOVETT, AND R.R TURNER. 1989. Atmospheric chemistry, deposition, and canopy interactions. P. 96-173 *in* Analysis of biogeochemical cycling processes in Walker Branch watershed, Johnson, D.W., and R.I. Van Hook (ed.). Springer-Verlag, New York.
LONDON, J.D. 1997. Forest statistics for Arkansas Counties-1995. USDA For. Serv. Resour. Bull. SRS-17. 53 p.
LUCKOW, K. 1998. Soil compaction monitoring of 20 timber harvest unit subplots on the Ouachita National Forest. *In* Appendix D of the Environmental. Assessment for Amendment No. 27 to the Forest Plan for Changing Applicable Forest Plan Standards and Guidelines Related to Soil Compaction and Normal Operating Seasons. May, 1998. USDA For. Serv. Ouachita National Forest, Hot Springs, AR.
LULL, H.W. 1959. Soil compaction of forest and range lands. USDA For. Serv. Misc. Publ. 768. Washington, DC. 32 p.
MASTERS, R.E., D.M. ENGLE, AND R. ROBINSON. 1993. Effects of timber harvest and periodic fire on soil chemical properties in the Ouachita Mountains. South. J. Appl. For. 18:139–145.
MCKEE, W.H., JR. 1982. Changes in soil fertility following prescribed burning on Coastal Plain pine sites. USDA For. Serv. Res. Pap. SE-234. 23 p.
MCKEE, W.H., JR. 1991. Long-term impacts of fire on coastal plain pine soils. P. 405–413 *in* Proc. of symp. on fire and the environment: Ecological and cultural perspectives. USDA For. Serv. Gen. Tech. Rep. SE-69.
MCWILLIAMS, W.H., R.M. SHEFFIELD, M.H. HANSEN, AND T.W. BIRCHE. 1986. The shortleaf resource. P. 9–24 *in* Murphy, P.A. (ed.). Proc. of symp. on the shortleaf pine ecosystem. Univ. Ark. Coop. Ext. Serv., Monticello, AR.
MILLER, E.L. 1984. Sediment yield and storm flow response to clear-cut harvest and site preparation in the Ouachita Mountains. Wat. Resour. Res. 20:471–475.
MILLER, E.L., R.S. BEASLEY, AND E.R. LAWSON. 1985. Stormflow, sedimentation, and water quality responses following silvicultural treatments in the Ouachita Mountains. P. 117–129 *in* Blackmon, B.G. (ed.). Proc. forestry and water quality: A mid-South symp., Little Rock, AR.
MILLER, E.L., R.S. BEASLEY, AND E.R. LAWSON. 1988. Forest harvest and site preparation effects on erosion and sedimentation in the Ouachita Mountains. J. Env. Qual. 17:219–225.
MILLER, P.E. A.J. HARTSELL, AND J.D. LONDON. 1993. Forest statistics for east Oklahoma counties-1993. USDA For. Serv. Resour. Bull. SO-144. 57 p.
MURPHY, P.A., AND R.M. FARRAR, JR. 1985. Growth and yield of uneven-aged shortleaf pine stands in the Interior Highlands. USDA For. Serv. Res. Pap. SO-218. 11 p.
POWERS, R.P., AND P.E. AVERS. 1992. Sustaining forest productivity through soil quality standards: A coordinated U.S. effort. P. 147–189 *in* Proc. of anthropogenic chemicals and soil quality criteria. A joint symp. of the Canadian Land Reclamation Association and the Canadian Society of Soil Science, Edmonton, Alberta, Canda.
PRESTON, D. 1997. Harvesting effects on the hydrology and drainage of a forested wetland. M.S. Thesis, Virginia Polytechnic Inst. and State Univ. 126 p.
RACHAL, J.M., AND B.L. KARR. 1989. Effects of current harvesting practices on the physical properties of a loessal soil in West-Central Mississippi. P. 527–532 *in* Proc. of the fifth bienn. south. silvic. res. conf., Miller, J.H. (ed.). USDA For. Serv. Gen. Tech. Rep. SO-74.
ROGERSON, T.L. 1985. Hydrologic responses to silvicultural practices in pine-hardwood stands in the Ouachita Mountains. USDA For. Serv. Res. Note SO-117. 5 p.
ROSSON, J.F., JR., AND J.D. LONDON. 1997. Forest statistics for Arkansas' Ouachita counties-1995. USDA For. Serv. Resour. Bull. SRS-10. 40 p.
SCHULTZ, R.P. 1997. Loblolly pine: The ecology and culture of loblolly pine (*Pinus taeda* L.). USDA For. Serv. Agric. Handbook. 713. 493 p.
SCOLES, S.R., S. ANDERSON, D.J. TURTON, AND E.L. MILLER. 1994. Forestry and water quality: A review of watershed research in the Ouachita Mountains. Okla. Coop. Ext. Water Qual. Series. Circ. E932. 29 p.
SILKWORTH, D.R., AND D.F. GRIGAL. 1982. Determining and evaluating nutrient losses following whole-tree harvesting of aspen. Soil Sci. Am. J. 46:626–631.
STOIN, H.R., B.B. KADMIN, AND L. THOMPSON. 1985. Changes in forest soils following clearcutting of pine forests in the Ouachita Mountains of Arkansas. Ark. Acad. Sci. Proc. 39:116–119.
STOKES, B.J., R.A. KLUENDER, R.A. WILLIAMS, AND J.F. KLEPAC. 1993. Assessment of costs and impacts for alternate harvesting methods in mixed stands. P. 655–662 *in* Proc. of the seventh bienn. south. silvic. res. conf., Brissette, J.C. (ed.). USDA For. Serv. Gen Tech. Rep. SO-93.
STOKES, B.J., R.A. KLUENDER, J.F. KLEPAC, AND D.A. LORTZ. 1995. Harvesting impacts as a function of removal intensity. P. 207–216 *in* Proc. of a symp. on forest operations and environmental protection, Stokes, B.J. (ed.). XX IUFRO World Congress, Tampere, Findland.
SWITZER, G.L., D.M. MOEHRING, AND T.A. TERRY. 1978. Clearcutting vs. alternative timber harvesting-stand regeneration systems: Effects on soils and environment of the South. P. 477–515 *in* Forest soils and land use, Youngberg, C.T. (ed.). Col. State Univ, Ft. Collins, CO.
TURTON, D.J., L.D. CLENDENEN, W.P. FOWLER, AND J.L. MICHAEL. 1997. Effects of silvicultural operations on the bulk density of stony soils in the Ouachita Mountains. USDA For. Serv., Final Rep.: Coop Agree. FS-SO-19-92-096. 17 p.
USDA FOREST SERVICE. 1990. Amended land and resource management plan. Ouachita National Forest. Vol. 1. USDA For. Serv., Ouachita Nat. For., Hot Springs, AR. 369 p.
WHEELER, G.L.,AND J.K. EICHMAN. 1991. The effects of forest management practices on soil nutrient status. USDA For. Serv., Final Rep.: Coop Agree. FS-SO-19-90-056. Ouachita Nat. For., Hot Springs, AR. 56 p.
YANAI, R.D. 1998. The effect of whole-tree harvest on phosphorus cycling in a northern hardwood forest. Biogeochemistry 17:1–22.
ZAK, B. 1961. Aeration and other factors affecting southern pines as related to littleleaf disease. USDA For. Serv. Tech. Bull. 1248. 30 p.