Impacts of Harvesting and Site Preparation

Moderator:

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SEDIMENT SOURCES TO THE CHATTOOGA RIVER

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Abstract—Sedimentation is a major water quality issue in Southern Appalachian streams, but sources of sediment in large watersheds have seldom been fully documented. The objectives of this study were (1) to identify and locate sources of sediment in the Chattooga River watershed, (2) to learn which subbasins within the watershed are primary contributors of sediment, and (3) to determine coverage and composition of fine sediments in pools of the river. We found that the Wild and Scenic River corridor was well vegetated in mature forests and contributed relatively little new sediment to the main stem of the river. Fine sediments dominated the substrate of pools in the river. Certain tributaries were major contributors of suspended and bed-load sediment. The majority (80 percent) of sediment sources were associated with graveled and unsurfaced roads. Timber harvests, pastures with unfenced riparian zones, developments, and recreation were important contributors of sediment at specific sites. If current sources of sediment are ameliorated, the river can recover from land-use abuses that have accelerated sedimentation over the past century.

INTRODUCTION

As one of the few remaining free-flowing rivers in the Southeast, the Chattooga is famous for its boating, fishing, wildlife, scenery, and aesthetic value. In 1974 Congress designated the Chattooga as one of America's Wild and Scenic Rivers, under the Wild and Scenic Rivers Act of 1968.

With the exception of Stekoa Creek, which has a sewage treatment plant, few point-source discharges into the Chattooga River exist. The principal threats to water quality in the watershed are from non-point sources. However, no comprehensive study has identified and located these sources of sediment in the Chattooga River watershed or quantified their relative contribution to sedimentation of the river.

Objectives of this study were to (1) identify and locate present sources of sediment to the Chattooga River, (2) learn which subbasins within the watershed are primary contributors of sediment, and (3) determine coverage and composition of fine sediments in pools of the river.

Study Area

The Chattooga River originates along the slopes of the Southern Appalachian Mountains in southwestern North Carolina and subsequently forms the scenic state boundary between Georgia and South Carolina. Its 180,000-acre watershed is underlain by crystalline bedrock composed primarily of gneisses, mica-schists, quartzes, and granites (Meyers and others 1986). Soils and the underlying saprolite are heavy in micaceous schist, a material that erodes easily once the vegetative cover and forest floor have been removed.

Forestation

Dry ridges and south slopes in the watershed are dominated by Virginia pine *(Pinus virginiana*), shortleaf pine (*P. echinata*), chestnut oak (*Quercus prinus*), and scarlet oak (*Q. coccinea*). Moist, cool, north slopes and coves often support white pine (*P. strobus*), eastern hemlock (*Tsuga canadensis*), yellow-poplar (*Liriodendron tulipifera*), and mixed mesophytic hardwood overstories with thick understories of rhododendron (*Rhododendron* sp.) and mountain laurel (*Kalmia latifolia*). Somewhat drier slopes support oak-pine mixtures as the dominant forest association (Meyers and others 1986).

The majority of the watershed is forested, with 68 percent of the subbasin held in national forests. In recent decades, residential development in the privately owned segments of the watershed has increased, leading to additional impacts on water quality. Public lands used for dispersed and developed recreation also have numerous signs of heavy use with resultant impacts on resource conditions. Agricultural activities include growing corn, apples, and cabbage, accompanied by poultry and livestock husbandry.

METHODS

Road Survey

Sediment sources that could be observed from unpaved roads were identified in a road survey. Approximately 92 percent of the open, public, unpaved roads in the watershed were inventoried by locating and describing obvious sedimentation problems on data sheets. Private roads were often not accessible. Sources of sediment that could be observed from paved roads were also noted, but traffic hazards prevented their detailed description.

Sediment sources were classified into one of six categories: (1) roads, (2) timber harvest, (3) agriculture (both crop farming and animal husbandry), (4) residential development, (5) recreational trails and facilities, and (6) any other type of soil-disturbing activity. The majority of sediment sources in the timber harvest category were associated with short (<1 mile) logging roads and skid trails.

The severity of each sediment source was subjectively ranked. Ranking was intended only to provide a scale of relative differences in impacts of different sediment sources. Locations of severe sources of sediment identified during the road survey were digitized into a GIS database and their locations mapped.

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Total Suspended Solids

Thirteen subbasins within the Chattooga River watershed, ranging in size from 906 to 24,460 acres, were selected for sampling the total suspended solids (TSS). These subbasins made up about 60 percent of the entire Chattooga watershed and contained a wide variety of road densities, land-use histories, and ownership patterns.

Depth-integrated water samples were collected twice monthly, usually during baseflow conditions, from each study subbasin from November 1993 through early April 1994. A vertical series of single-stage samplers was used to collect stormflow samples when erosion and sediment transport were most likely to occur. The highest sampler was positioned just above the level of bank-full flow. This sedimentation monitoring program was based on a similar monitoring program of TSS that has been successfully used on over 40 sites in the Southern Appalachians by Duke Power Company (Braatz 1994). Concentrations of suspended solids are expressed in parts per million (ppm) rather than milligrams per liter, since we use English units in this paper.

Fine Sediments in the Substrate

Coverage of pool bottoms by fine-sediment deposits, i.e., deposits dominated by sand and finer materials, was estimated using low-altitude videography. Video footage was shot from a helicopter on March 14, 1994 with an Ikegami HL55 Betacam. Average helicopter height above the river varied from 150 to 200 feet depending on conditions. About 58 percent of the Beta videotape could be analyzed for substrate coverage by fine sediments. Glare from sunlight, helicopter angle, and other factors prevented analysis of the remainder.

Within reaches of the river, the percentage of pool area in fine sediment deposits was visually estimated using representative frames from the Beta tape and an on-screen grid. An average flight speed was calculated and used to convert numbers of frames (30 per see) to linear stream lengths.

Four locations were ground-truthed to confirm that videotape estimates of the area covered by fine sediment deposits were reliable. Grab samples of the substrate material were also taken from shallow pools at these locations to determine the particle-size distribution of material classified as fine sediment in the visual estimates (Van Lear and others 1995).

RESULTS

Road Survey

The road survey of 205 miles of open, unpaved roads in the Chattooga Watershed documented 1,106 observable sources of sedimentation, an average of 5.68 sediment sources per mile. The impact of some land uses causing sedimentation may have been underestimated because only sediment sources visible from surveyed roads were included in the survey. However, an aerial reconnaissance of much of the watershed by helicopter prior to leaf development in March 1994 did not identify any significant sediment sources that would have been missed by the road survey.

The greatest frequency of sediment sources (80 percent) in the watershed was associated with gravel and unsurfaced roads (fig. 1). Among the commonly noted causes of sedimentation from roads were: (1) poor location and design; (2) rutting, gullying, and sheet erosion of road surfaces; (3) road bank slumping; (4) erosion of roadside ditches; (5) stream and drainage crossings; (6) poor placement of ditch turnouts or outlets; and (7) improperly located or functioning culverts. Approximate locations of major sediment sources were digitized into a GIS data base so that landowners and managers could find and correct these sources.

About 9 percent of the sediment sources observed during the road survey were attributed to timber harvesting operations. The great majority of these sources were associated with short (generally less than 1 mile) logging access roads that connected to the multipurpose roads, rather than to the cutting of timber.

Agriculture accounted for 4.5 percent of the identified sediment sources from the road survey. Most observed agricultural impacts were associated with grazing in the riparian zones of small to intermediate perennial streams. About 3 percent of the noted sediment sources were related to residential development. These sources were generally new house sites and the driveways leading to these sites. Recreational impacts accounted for only a small percentage (2.6 percent) of the observed sources of sediment. However, many roads remain open for public access and recreational use. Sediment sources falling in the “other” category ranged from landfills to beaver impacts.

Total Suspended Solids

Stekoa and Big Creeks had by far the highest levels of stormflow TSS of any of the 13 study streams, with both storm event maximums and storm event means averaging over 2000 ppm and single extreme samples of 21,018 and 16,462 ppm (table 1). Estimates suggest that 80 percent of the total Chattooga River sediment load can be associated with these two streams. Whetstone had the third highest level of stormflow TSS.

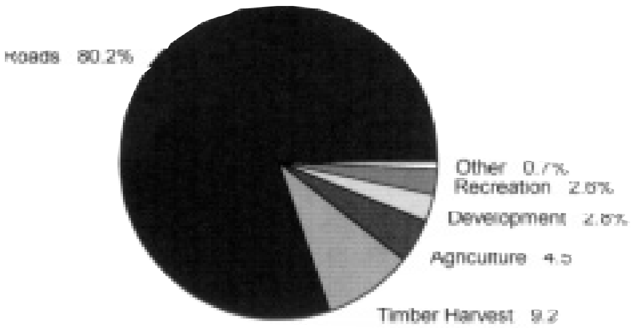

Figure 1—Distribution of sediment sources observable from a survey of public, unpaved roads in the Chattooga River watershed.

Table 1—Relative ranking of 13 subbasins within the Chattooga River watershed based on average storm event maxima for total suspended sediment (TSS)

Subbasin	Ranking	Avg. of storm event max. TSS[1]	Storm flow mean TSS	Max. TSS	Base flow mean TSS
		- - - - - - - - - - - *Ppm*	- - - - - -	- - - - - -	- - - - - -
Stekoa	1	3057 (8)	2501 (18)	21018	13 (10)
Big	2	2197 (9)	2255 (19)	16462	10 (10)
Whetstone	3	619 (6)	734 (8)	1523	16 (10)
Warwoman	4	167 (9)	128 (20)	359	10 (10)
King	5	151 (5)	151 (5)	489	23 (9)
Reed	6	150 (7)	118 (12)	476	10 (9)
East Fork	7	144 (7)	94 (15)	503	16 (9)
Long	8	112 (9)	99 (15)	274	11 (10)
Bull Pen	9	93 (6)	71 (23)	142	11 (7)
Harden	10	84 (5)	93 (7)	300	10 (9)
Holcomb	11	66 (9)	39 (30)	182	13 (9)
S. Fowler	12	65 (6)	57 (10)	132	9 (8)
Overflow	13	64 (9)	51 (21)	138	7 (10)

[1] Mean with number of samples in parenthesis.

There was no TSS sampling station on the West Fork of the Chattooga, although its three major tributaries (Big, Overflow, and Holcomb) were sampled. During high-intensity storms, steep-gradient sections of overflow Creek Road, just above the bridge on Forest Service Road 86, flushes heavy sediment loads at numerous locations into the West Fork. This section is downstream of the TSS sampler on Holcomb Creek. Warwoman, King, Reed, East Fork, and Long Creeks had average TSS storm event maximums that ranged between 167 and 110 ppm. Streams with the lowest stormflow TSS levels included Bullpen, Harden, Holcomb, S. Fowler, and Overflow Creeks (above the confluence with Clear Creek).

Stormflow TSS levels of subbasins in the Chattooga Watershed varied widely in their concentration of suspended sediment. However, baseflow TSS conditions were similar across all study subbasins, with averages ranging from 7 to 23 ppm.

Fine Sediments

The river was extremely clear at normal flow when the low-altitude helicopter videography was conducted. Fine sediments could clearly be detected in the two upper sections on the videotape (table 2). Fine sediments covered about 63 percent of pool substrate in Section I. The percentage of the pool substrate covered by fine sediments increased in Section II (Russell Bridge to Dick Creek) to 85 percent due to sediment inputs from tributaries and decreased gradient.

Because of greater pool depth, water turbulence, glare, and helicopter angle in the steeper Section III, fine sediment coverage could not be estimated with confidence. The

Table 2—Coverage of pool substrates of the Chattooga River by fine sediments, as estimated from analysis of aerial videotape

Section[1]	Gradient	No. of pools sampled	Ave. coverage of pool substrate by fine sediment
	Feet/mile		- - - *Percent* - - -
I	44	22	63
II	15	23	85

[1] I = Bull Pen Bridge to Russell Bridge; II = Russell Bridge to Dick Creek.

stream channel in Section III is tightly constrained by geology. Stekoa Creek, the major contributor of sediment and other pollutants to the river, enters midway through this section.

DISCUSSION

Road Survey

Open graveled and unpaved roads were the major source of sediment surveyed in the Chattooga River watershed. Many of these roads evolved from old wagon trails near the turn of the century and frequently occur on flatter terrain, which often is along stream courses. From a water quality standpoint, roads adjacent to streams are in the worst possible location.

Many of the unpaved, open roads surveyed were within national forests, including about 68 percent of the watershed. Multi-purpose unpaved roads with the greatest frequency of sediment sources were generally those with heavy vehicular traffic. Heavy vehicle use, especially during wet weather, causes rutting of road surfaces which increases the need for maintenance. Road maintenance operations are major causes of sedimentation of streams in the Chattooga River watershed, especially where vegetative buffer strips are inadequate to filter loosened sediments. Roads adjacent to streams are especially prone to deliver sediments to the stream.

Unpaved, graveled roads, because of their location, extent, heavy use, and frequent maintenance, are the major source of sediment in the Chattooga River watershed. The frequency with which roads crossed drainages (culvert density) has been positively correlated with the amount of fine substrate and embeddedness in Wyoming trout streams (Eaglin and Hubert 1993). Similar findings have been noted by Durniak and Ruddell (1990) in north Georgia and Swift (1984) in western North Carolina.

Unpaved roads with a high frequency of travel should be surfaced with a coarse gravel foundation for stability prior to adding a finer surfacing material. Aggregates with a high proportion of fine material should be avoided. Placement of large gravel in roadside ditches would reduce the need for maintenance and protect this very sensitive portion of the road. Strict adherence to Best Management Practices guidelines and appropriate use of inexpensive water control features (Tew and others 1985, Swift 1987) would minimize sedimentation problems associated with unpaved roads.

A relatively small proportion (9 percent) of total observed sediment sources was attributed to timber harvesting. Most of these sources were associated with short spur roads accessing the harvest site. Cutting of timber per se rarely causes erosion; rather, the cause is generally the transportation system required to remove the harvested trees (Douglass 1974, Kochenderfer and Aubertin 1975, Hewlett 1979). If timber removal is the primary use, roads should be surfaced with aggregate dominated by large rock (particles 3 to 4 inches in size). These temporary-use roads should normally be closed or maintained for high-clearance vehicles following harvest.

Gated Forest Service roads whose surfaces had been graveled and vegetated were no longer a significant source of sediment to adjacent streams. These roads are open to foot traffic but closed to vehicles, except in cases of extreme need. They become excellent linear wildlife strips and are aesthetically attractive. Periodic mowing keeps them accessible for forest management emergencies or other needs.

Closing those unpaved, graveled roads that are not heavily used or necessarily kept open would reduce impacts on water quality. Closed roads remain as valuable assets used by hunters, fishermen, hikers, and others with minimal impact on streams of the area. Although some unpaved, graveled roads, because of design, location, or other factors, do not contribute significant sedimentation to streams, many do. Often these roads or sections of them are the major source of sediment to a particular stream. A significant reduction in the density of open graveled and unsurfaced roads would probably have a greater influence on water quality in the Chattooga River watershed than any other single recommendation.

Paved roads also contribute sediment to streams in the Chattooga River watershed, especially during and following their construction/reconstruction and right-of-way maintenance phases. Deeply entrenched ditches along many paved roads are evidence that they have been chronic sediment producers for decades. Federal and state highway agencies should consider the benefits of stable vegetation as an effective cover to prevent erosion and minimize maintenance costs. Routine pulling of road ditches during maintenance is often unnecessary and disruptive to bank stability and water quality.

Stream bank fencing is a simple and effective way for farmers to improve water quality, maintain soil productivity, and protect their livestock from waterborne bacteria. Soil and water conservation districts, State environmental, water, forestry, and agricultural agencies are good contacts for discussing cost-share opportunities available to private landowners to protect streams and improve water quality. Work on national forest roads is conducted through various road construction, reconstruction, and maintenance funds. Timber harvest activities also contribute to road costs.

Sedimentation from development is likely to escalate in the future. Strict enforcement of Section 404 of the Federal Clean Water Act and a State and 12 local sediment control laws would reduce development-related sedimentation in the Chattooga River watershed. Best Management Practices, when properly applied, are effective measures in protecting water quality.

The relative contribution of recreational sources of sediment (2.6 percent) is misleading. Recreationists of all pursuits, including rafters, anglers, hunters, hikers, campers, and scenic drivers, account for most of the traffic on the road network. Roads would require less maintenance and contribute far less sediment if they were not heavily used by recreationists.

Sedimentation

Fine sediments exert detrimental effects on benthic macroinvertebrates by altering and degrading critical habitats (Reiser and White 1988, Wesche and others 1989). Excessive fine sediments cover and fill interstices of gravel and cobble substrates, transforming the stream bottom to a habitat composed of small unstable particles which can be utilized by only a relatively few species. Species characteristic of stony-bottomed riffles may disappear, as will many species whose food supply is covered by sediment (Bjornn and others 1977, Minshall 1984, Wallace and others 1992).

An increase in fine sediments within stream substrates generally has a negative impact on salmonids. Fine sediments prevent oxygen from reaching eggs, trap fry in the substrate, and retard the removal of toxic compounds from reads (Waters 1995). In addition to adverse effects on reproduction, excessive fine sediments can be detrimental to the habitat and survival of adult trout (Chapman 1988, Young and others 1991, Waters 1995). Both suspended and settled fine sediments adversely affect trout and other fish species (Young and others 1991, Waters 1995). Although high water temperatures, low fertility, and lack of coarse woody debris limit production of trout streams in the Southern Appalachians (Habera and Strange 1993), it is also reasonable to assume that excessive fine sediments adversely affect trout production in the Chattooga River.

High suspended-sediment levels were documented in certain tributaries of the Chattooga River. Aerial videography showed that tributaries also contribute heavy bed-loads of fine sediments to the river. Until sedimentation problems of tributaries are corrected, it will be impossible to reduce impacts of sedimentation on the aquatic community within the main river. Concentration of restoration efforts in Big Creek and Stekoa Creek, the major contributors of sediment, appears to be the proper approach to improve water quality in the Chattooga River. However, contributions from lesser tributaries should not be dismissed.

The single-stage samplers used in this study to sample TSS were effective and inexpensive, yet simple to install and use. They could be used in streamwatch programs by volunteer organizations to monitor water quality, although users should be aware of the limitations of the technique. The low levels of baseflow TSS from all 13 tributaries emphasize the importance of sampling representative storm events to obtain a realistic comparison of suspended sediment transport by different streams (Braatz 1994).

Because of the geology of the watershed, much of this stored sediment is undoubtedly a natural feature of the river. It is equally certain that man's activities have contributed large quantities of sediment to the river. Because of the huge quantities of sediment stored in the channel and its embeddedness in the substrate, it may take decades or even centuries for the river bottom to approach full recovery, assuming that anthropogenic sources of sediment are minimized. Nevertheless, now is the time to initiate a major watershed effort to control sedimentation and allow the river and its tributaries to begin progressing toward their full biological and aesthetic potential.

CONCLUSIONS

This study utilized various methods, including a road survey, water quality sampling, helicopter videography, and substrate sampling, to evaluate sedimentation in the Chattooga River watershed. Major conclusions are:

- Unpaved multipurpose roads were associated with about 80 percent of the sediment sources observed from roads in the Chattooga River watershed. Other sources of sediment, although perhaps locally important, were relatively minor.
- Heavy recreational use of these unpaved gravel roads contributes to their sedimentation potential through heavy trafficking and by increasing the need for maintenance.
- Suspended sediment levels were highest in subbasins heavily impacted by roads, pastures with unfenced riparian zones, and development.
- Land-uses in drainages of major tributaries that expose, compact, or trample mineral soil are the major causes of high stormflow levels of suspended sediment in the Chattooga River. The Wild and Scenic corridor of the main stem of the river contributes relatively little new sediment.
- A long history of land use within the Chattooga River watershed has significantly contributed to excessive sedimentation of the river. A major effort by all landowners, both public and private, and users, to reduce and reclaim sources of sedimentation, could quickly initiate a recovery of the watershed and lead to continuing enhancement of resource values associated with the river and its tributaries.

ACKNOWLEDGMENT

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LITERATURE CITED

Bjornn, T.C.; Brusven, M.A.; Molnau, M.P.; Milligan, J.H. 1977. Transport of granitic sediment in streams and its effects on insects and fish. Moscow, ID: Forest, Wildlife, and Range Experiment Station, University of Idaho. 43 p.

Braatz, D.A. [In press]. An inexpensive stormflow monitoring program that provides critical water quality data on Southern Appalachian streams. Proceedings, Appalachian rivers and watershed symposium; 1994 June 3-6; Morgantown, WV.

Chapman, D.W. 1988. Critical review of variables used to define effects of fines in reads of large salmonids.

Transactions of the American Fisheries Society. 117:1-21.

Douglass, J.E. 1974. Watershed values important for land-use planning on southern forests. Journal of Forestry. 72:617-621.

Durniak, J.P. 1987. A fisheries survey of the Upper Chattooga River. Final report. Dingell-Johnson Project F-25. Atlanta, GA: Georgia Department of Natural Resources.

Durniak, J.P.; Ruddell, W.R. 1990. Evaluation of trout fingerling stocking in small headwater trout streams. Atlanta, GA: Georgia Department of Natural Resources, Game and Fish Division. 52 p.

Eaglin, G.S.; Hubert, W.A. 1993. Effects of logging and roads on substrate and trout in streams of the Medicine Bow National Forest, Wyoming. North American Journal of Fisheries Management. 13:844-846.

Habera, J.W.; Strange, R.J. 1993. Wild trout resources and management in the Southern Appalachians. Fisheries. 18:6-13.

Hewlett, J.D. 1979. Forest water quality: an experiment in harvesting and regenerating Piedmont forests. Georgia Forest Resources Paper. Athens, GA: University of Georgia Press. 183 p.

Kochenderfer, J.N.; Aubertin, G.M. 1975. Effects of management practices on water quality and quantity. In: Municipal watershed management symposium Proceedings, Gen. Tech. Rep. NE-13. Upper Darby, PA: USDA Forest Service.

Meyers, R.K.; Zahner, R.; Jones, S.M. 1986. Forest habitat regions of South Carolina from Landsat imagery. Clemson, SC: Clemson University, Department of Forestry. Forest Research Series 42. 31 p.

Minshall, G.W. 1984. Aquatic insect substratum relationships. In: Resh, V.H.; Rosenberg, D.M., eds. The ecology of aquatic insects. New York: Praeger: 358-400.

Reiser, D.W.; White, R.G. 1988. Effects of two sediment size-classes on survival of steelhead and chinook salmon eggs. North American Journal of Fisheries Management. 8:432-437.

Swift, L.W. 1987. Forest access roads: Design, maintenance, and soil loss. In: Swank, W.T.; Crossley, D.A., Jr., eds. Forest hydrology and ecology at Coweeta. New York: Springer-Verlag: 313-324.

Swift, L.W., Jr. 1984. Gravel and grass surfacing reduces soil loss from mountain roads. Forest Science. 30:657-670.

Tew, H.C.; Price, L.C.; Swift, L.W. 1985. The layman's guide to private access road construction in the Southern Appalachian Mountains. U.S. Department of Agriculture, Soil Conservation Service, Forest Service, and Tennessee Valley Authority. Waynesville, NC: Haywood Press, Inc.

Van Lear, D.H.; Taylor, G.B.; Hansen, W.F. 1995. Sedimentation in the Chattooga River watershed. Clemson University, Department of Forest Resources. Tech. Pap. 19. 61 p.

Wallace, J.B.; Webster, J.R.; Lowe, R.L. 1992. High-gradient streams of the Appalachians. In: Hackney, C.T.; Adams, S.M.; Martin, W.H., eds. Biodiversity of the Southeastern United States: aquatic communities. New York: John Wiley & Sons, Inc.

Waters, T.F. 1995. Sediment in streams — Sources, biological effects, and control. American Fisheries Society Monograph 7. Bethesda, MD: American Fisheries Society. 251 p.

Wesche, T.A.; Reiser, D.W.; Hasfurther, V.R. [and others]. 1989. New technique for measuring fine sediment in streams. North American Journal of Fisheries Management. 9:234-238.

Young, M.K.; Hubert, W.A.; Wesche, T.A. 1991. Selection of measures of substrate composition to estimate survival to emergence of salmonids and to detect changes in stream substrates. North American Journal of Fisheries Management. 11:339-346.

GROWTH AND DEVELOPMENT OF WATER TUPELO (*NYSSA AQUATUCA*) - BALDCYPRESS (*TAXODIUM DISTICHUM*) FOLLOWING HELICOPTER AND SKIDDER HARVESTING: 10-YEAR RESULTS

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Abstract—Ground-based timber harvesting operations in forested wetlands have the potential to cause soil disturbances. Similar soil disturbances on upland sites have been linked to reduced site productivity, but the effects of such disturbances on the long-term site productivity of bottomland hardwoods is not well documented. In 1986, a long-term research project was established to compare the effects of helicopter and skidder timber harvesting on the regeneration, growth, and development of naturally regenerated water tupelo (*Nyssa aquatica*) - baldcypress (*Taxodium distichum*) stands. At stand age 10 years, both treatment areas have well-stocked, vigorously growing stands composed of coppice-regenerated water tupelo, Carolina ash (*Fraxinus caroliniana*), baldcypress, and seed-origin black willow (*Salix nigra*). Although both areas are well stocked, the skidder treatment favored the growth of water tupelo, while the helicopter treatment had densities and growth rates for Carolina ash. Apparently, the initial effects of the skidder traffic puddled soils, causing more reduced soil conditions that removed less flood-tolerant species, leaving the very flood-tolerant water tupelo. Stand growth parameters suggest that both treatments will produce stands that will be similar to the previous stands in terms of species and volume. Recovery in this area was speeded by annual inputs of nutrient-rich sediment and the shrink-swell nature of the soil.

INTRODUCTION

Forested wetlands, such as bottomland hardwoods, have unique landscape positions and ecological processes that allow them to provide numerous benefits to society. Examples of societal values include storm water storage, provision of habitat, improvement of water quality, and production of timber (Walbridge 1993). Although timber harvests have occurred in these areas for over 200 years, the effects of harvesting on subsequent wetland ecosystem processes have been evaluated only over the past decade (Lockaby and others 1997). The objectives of this research project are to evaluate the effects of helicopter and rubber-tired skidder timber harvests on subsequent stand growth and development after 10 growing seasons.

METHODS

Study Site

The study site is located along the Tensaw River within the Mobile-Tensaw River Delta in Baldwin County, AL. Prior to treatment installation, the stand had a two-aged overstory as the result of previous float and pull-boat harvesting operations that occurred in the mid-1800's and early 1900's, respectively (Aust 1989, Mader 1990). The majority of the stand was composed of 70-year-old water tupelo (*Nyssa aquatica*) and baldcypress (*Taxodium distichum*), while a few older residual trees were present. The overstory was composed of approximately 85 percent water tupelo, 10 percent baldcypress, and 5 percent Carolina ash (*Fraxinus caroliniana*). The site had a site index (50 years) of 85 feet for water tupelo and produced approximately 80 cords per acre of merchantable timber. The site floods annually; average annual flood peaks exceed 3 feet in depth (U.S. Army Corps of Engineers 1985-1996). Levy is the dominant soil series (fine, mixed, acid, thermic Typic Hydraquents) (USDA Natural Resources Conservation Service 1997).

Treatments

Pretreatment site characterization was conducted during the spring, summer, and fall of 1986 to ensure that the stands were homogeneous in terms of hydrology, soils, and vegetation (Aust 1989, Mader 1990). During late fall 1986, three disturbance treatments were installed in a three 3 by 3 Latin squares design. The Latin square statistical design was used so that gradients parallel to and perpendicular to the river could be examined. Each of the three disturbance treatments had nine replications within this design.

Each of the 27 treatment plots measured approximately 3 chains by 3 chains, containing slightly less than 1 acre. The entire treatment area (27 treatment plots) received chainsaw felling and helicopter removal of all merchantable stems and nonmerchantable stems greater than 2 inches in diameter at breast height (d.b.h.). This level of treatment comprised the helicopter treatment and nine of the treatment plots remained in this state.

After helicopter timber removal was completed, the skidder treatment was installed on nine additional plots. These plots received trafficking with a Franklin 105 cable skidder equipped with 34-inch-wide rubber-tires. The skidder simulated harvesting operations by trafficking across the skidder treatment plots until approximately half of each skidder plot was rutted to an average depth of 1 foot. Local procurement foresters stated that the results were very similar to normal skidding on such sites.

The remaining nine plots were treated with glyphosate herbicide during the first two growing seasons following

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harvest. This herbicide treatment controlled vegetative regrowth (glyphosate treatment), so that the effects of the lack of vegetation on early restoration processes could be evaluated as reported in Aust and Lea (1991).

Although not included within the experimental design because of helicopter logistics, a reference area was left downstream from the disturbance treatments. This area has the same hydroperiod, soil, and vegetation as the disturbance area did before treatments were installed.

The glyphosate treatment area is currently a scrub-shrub wetland dominated by herbaceous vegetation. While this is an interesting successional state, it is not an operationally feasible, nor desirable, forest. The older reference area has similar species composition as within the helicopter and skidder treatments, but the difference in age makes comparison difficult. Therefore, within this paper, only the helicopter and skidder treatments will be considered. Additional details concerning the original study site conditions; treatment installation; 1-year, 2-year, 7-year, and 8-year measurements and results are available (Aust 1989, Aust and Lea 1991, 1992, Aust and others 1991, 1997, Mader 1990, Mader and others 1989, Szabo and others 1994, Zaebst 1997).

Ten-Year Data Collection and Analyses

Circular measurement subplots (1/30 acre) were established in each of the nine replications of the skidder and helicopter treatment plots. For each overstory stem (d.b.h. > 1.49 inches) in the subplot, the following attributes were measured: species, azimuth from plot center, d.b.h., total height, crown class, tree vigor, and number of stems per stump. After field work was completed, total biomass for each species was determined using biomass equations developed on these sites by Mader (1990) and Zaebst (1997). Standard analyses of variance were conducted for the three 3 by 3 Latin squares (Steel and Torrie 1980). If significant treatment differences were detected by the analysis of variance (alpha < 0.05), then treatments were separated with a Fishers protected LSD test.

RESULTS AND DISCUSSION

Sources of Regeneration

Regeneration levels following the clearcutting with helicopter and skidder treatments were very successful, primarily due to abundant coppice regeneration. Over 90 percent of the water tupelo, Carolina ash, and baldcypress remaining after 10 growing seasons were of stump origin. Black willow was the only seed-origin species still present in the overstory after ten growing seasons. The previous stand was also dominated by coppice origin, with two and three stems per stump being common and evident even after 70 years. The average numbers of stems per stump that were in an overstory position at age 10-years are presented in table 1.

The success of the coppice regeneration was not a foregone conclusion. Kennedy (1982) had cautioned that coppice of water tupelo was erratic and unreliable. Larsen (1980) reported that baldcypress sprouting is of minor importance, and Ewel (1996) found that only 17 percent of pondcypress sprouted after harvests. The success of the water tupelo coppice was probably enhanced by several factors. During the harvesting operation, sawyers felled the trees in standing water and cut relatively high stumps. These higher stumps increased the initial number of stems per sprout, but the higher stumps have not led to undue windthrow at 10 years. Another important factor explaining the success of the coppice is the annual inputs of sediment (Aust and others 1991, 1997). These inputs have facilitated coppice growth by ensuring adequate nutrition and by physically reducing the height of the stumps above the soil surface, actually masking the higher stumps.

Table 1—Helicopter and skidder treatment effects on average number of sprouts per stump for species remaining in the overstory after 10 growing seasons

Common name (*Genus species)*	Helicopter	Skidder
	---Sprouts per stump---	
Black willow (*Salix nigra*)	1.0[a]	1.0[a]
Water tupelo (*Nyssa aquatica*)	4.2	4.7
Carolina ash (*Fraxinus caroliniana*)	3.4	2.6
Baldcypress (*Taxodium distichum*)	2.2	2.2
Red maple (*Acer rubrum*)	1.4	1.2
Water elm (*Planara aquatica*)	3.9	3.5

[a] Black willow regenerated from seed only.

Species Growth and Yield

Four species composed over 97 percent of the overstory density: black willow, water tupelo, Carolina ash, and baldcypress, with two species, red maple and water-elm, being less common associates (table 2). This species mix is relatively common for water tupelo-baldcypress stands in

Table 2—Helicopter and skidder treatment effects on the density of overstory species after 10 growing seasons (different letters represent significant treatment effects on the density of a species at alpha levels of 0.05)

Common name (*Genus species)*	Helicopter	Skidder
	----Stems per acre----	
Black willow (*Salix nigra*)	436 a	506 b
Water tupelo (*Nyssa aquatica*)	476 a	506 b
Carolina ash (*Fraxinus caroliniana*)	683 b	447 a
Baldcypress (*Taxodium distichum*)	60	80
Red maple (*Acer rubrum*)	16	40
Water elm (*Planara aquatica*)	27	7
Total	1698	1826

deep alluvial swamps (Larsen 1980). Black willow was the only overstory species present in the 10-year-old stand that had not been present prior to harvest. Black willow is a very intolerant, pioneer species that commonly seeds into disturbed bottomlands (Meadows and Stanturf 1997), but the species is relatively short-lived and will eventually be replaced by longer-lived, or less intolerant species (Krinard 1980). There were no significant differences in regeneration of black willow between the helicopter and skidder harvested areas after 10 years, although the skidder treatment had favored willow regeneration during the first two growing seasons (Mader 1990, Mader and others 1989).

The helicopter and skidder treatment areas did have significantly different densities of water tupelo and Carolina ash (table 2). The skidder treatment had 57 percent more water tupelo stems per acre, while the helicopter treatment had 53 percent more Carolina ash stems per acre. These differences are explained by the treatment effects on soil and hydrologic properties at 1 and 2 years (Aust 1989, Mader 1990).

The skidder treatment plots had average trafficked areas of 52 percent and the ruts averaged over 1 foot in depth (Aust 1989). The soils of the skidder treatment had been trafficked during saturated soil conditions and the soil had literally flowed from the ruts, a disturbance referred to as puddling. This destroyed soil macropore space and reduced saturated hydraulic conductivity values (table 3), causing soil water movement to be restricted. Soil oxygen values and soil redox potentials were also lower within the skidded treatment areas (Aust 1989, Aust and Lea 1992). Although not statistically significant, the water tables within the skidded plots tended to be closer to the soil surface than in the helicopter plots. This trend continued as late as 8 years after harvest (Aust and others 1997, Szabo and others 1994). The wetter and more reduced conditions within the skidder treatment favored the growth of the more flood-tolerant water tupelo (Larsen 1980) by reducing competition from other species, while the less reduced conditions within the helicopter treatment allowed the Carolina ash to regenerate more successfully.

Table 3—Average saturated hydraulic conductivity, soil oxygen percentage, and redox potential (pH 6.0) in the helicopter and skidder treatments for the first two growing seasons (1987, 1988) (different letters represent significant treatment effects at alpha levels of 0.05)

Treatment	Average saturated hydraulic conductivity	Average soil oxygen	Average redox potential (at pH 6.0)
	Inches/hour	*Percent*	*mV*
Helicopter	3.3 b	2.2 b	220 b
Skidder	2.9 a	1.4 a	125 a

Growth characteristics of the water tupelo and Carolina ash were also affected by the helicopter and skidder treatments. Average diameter, total height, basal area, and total biomass of water tupelo were significantly increased within the skidder treatments. Conversely, average diameter, height, basal area, and biomass of Carolina ash were favored by the helicopter treatment (tables 4, 5, 6, 7). These results were similar to those observed at age 7 years (Aust and others 1997, Zaebst 1997); however, the percentage of difference between the species was less at 10 years, indicating that treatment differences for these two species will be minimized further over time. This conclusion assumes that the belowground carbon allocation within the helicopter and skidder treatment areas are similar, which may not be correct. Powell and Day (1991) found that a higher percentage of belowground net primary productivity was allocated to water tupelo that were grown under drier soil conditions. Sediment deposition has probably helped to mitigate the differences between the helicopter and skidder treatment results (table 8).

Table 4—Helicopter and skidder treatment effects on the average diameter at breast height of overstory species after 10 growing seasons (different letters represent significant treatment effects on the density of a species at alpha levels of 0.05)

Common name (*Genus species)*	Helicopter	Skidder
	- - - - - -Inches- - - - - -	
Black willow (*Salix nigra*)	3.5	3.7
Water tupelo (*Nyssa aquatica*)	2.9 a	3.3 b
Carolina ash (*Fraxinus caroliniana*)	1.9 b	1.5 a
Baldcypress (*Taxodium distichum*)	2.0	1.9
Red maple (*Acer rubrum*)	2.0	2.0
Water elm (*Planara aquatica*)	1.7	1.8

Table 5—Helicopter and skidder treatment effects on average total height of overstory species after 10 growing seasons (different letters represent significant treatment effects on the density of a species at alpha levels of 0.05)

Common name (*Genus species)*	Helicopter	Skidder
	- - - - - - Feet - - - - - -	
Black willow (*Salix nigra*)	34.8	35.1
Water tupelo (*Nyssa aquatica*)	27.9 a	30.2
Carolina ash (*Fraxinus caroliniana*)	26.0 b	21.2 a
Baldcypress (*Taxodium distichum*)	14.7	14.0
Red maple (*Acer rubrum*)	27.9	21.3
Water elm (*Planara aquatica*)	21.3	16.7

Table 6—Helicopter and skidder treatment effects on the basal area of overstory species after 10 growing seasons (different letters represent significant treatment effects on the density of a species at alpha levels of 0.05).

Common name (*Genus species)*	Helicopter	Skidder
	---Square feet per acre---	
Black willow (*Salix nigra*)	29.1 a	37.8 b
Water tupelo (*Nyssa aquatica*)	21.8 a	44.3 b
Carolina ash (*Fraxinus caroliniana*)	13.5 b	5.5 a
Baldcypress (*Taxodium distichum*)	1.3	1.6
Red maple (*Acer rubrum*)	0.3	0.9
Water elm (*Planara aquatica*)	0.4	0.1
Total	66.4 a	90.2 b

Table 7—Helicopter and skidder treatment effects on the woody biomass in overstory species after 10 growing seasons (different letters represent significant treatment effects on the density of a species at alpha levels of 0.05).

Common name (*Genus species)*	Helicopter	Skidder
	-----Tons per acre-----	
Black willow (*Salix nigra*)	13.27	16.41
Water tupelo (*Nyssa aquatica*)	11.85 a	18.09 b
Carolina ash (*Fraxinus caroliniana*)	2.08 b	1.17 a
Baldcypress (*Taxodium distichum*)	1.69	2.17
Red maple (*Acer rubrum*)	0.19	0.43
Water elm (*Planara aquatica*)	0.28	0.06
Total	29.36 a	38.33 b

Table 8—Average and total accumulated sediment in the helicopter and skidder treatments after 10 growing seasons (different letters represent significant treatment effects at alpha levels of 0.05)

Treatment	Average annual sedimentation	Total sedimentation for 10 years
	Inches/year	*Inches*
Helicopter	0.41	4.1
Skidder	0.32	3.2

CONCLUSIONS

Regeneration at stand age 10 years was good in both the helicopter and skidder treatments. With the exception of black willow, coppice regeneration dominated the overstory canopy within both treatments. The only significant seed-regenerated species, black willow, is a shade-intolerant, pioneer species. Due to its naturally short life expectancy, black willow is expected to experience heavy mortality within the next 20 to 40 years. At that time, the species composition in the helicopter and skidder treatments will be similar to the preharvest stand. Both treatments will have an overstory dominated by water tupelo, with baldcypress and Carolina ash being less important overstory associates.

At stand age 10, the skidding treatment favored the growth of water tupelo at the expense of Carolina ash. We hypothesize that this treatment effect was caused by the initial effects of the skidding treatment on site hydrology. The skidder traffic rutted and puddled the soils, initially reducing soil water movement and aeration as compared to the soils in the helicopter treatment. The more reduced conditions in the skidder treatment favored the very flood-tolerant water tupelo at the expense of the slightly less flood tolerant Carolina ash. We hypothesize that, over time, the treatment differences between the growth of water tupelo and Carolina ash will lessen. As canopy stratification increases, the naturally slower growing Carolina ash will fall into the midstory canopy within both treatments.

At present, the skidder treatment unexpectedly produced more total aboveground biomass (table 7) than did the less soil disturbing helicopter treatment. There are several plausible explanations for this phenomena. Perhaps the increase in microtopography within the skidded treatment area increased the proportion of aerated soils that roots can exploit, an effect similar to mechanical site preparation for pine on wet sites. Perhaps the reduced conditions in the skidder treatment favored aboveground biomass production at the expense of belowground biomass production, as found by Powell and Day (1991). Also, the reduced soil conditions within the skidder treatment area have favored the water tupelo and intraspecific patterns of competition, while the helicopter treatments have favored a pattern of interspecific competition. Additionally, the sedimentation patterns and clay mineralogy of the site make these site more difficult to damage with traffic as compared to non-alluvial, 1:1 clay-dominated sites. The annual sediment deposition in both treatments enhances soil nutritional levels and fills in ruts. The shrink-swell clays also allowed the rutted soils to recover saturated hydraulic conductivity rapidly. Hopefully, we will establish the exact processes that facilitated the rapid recovery in future studies, but the differences between the helicopter and skidder treatment areas will probably lessen as the rotation proceeds.

Overall, the stand composition, growth rates, and biomass accumulation in the helicopter and skidder treatment sites indicate that recovery is progressing rapidly. If expected patterns of stand development occur, the future stands will have species and volumes similar to the previous stands.

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LITERATURE CITED

Aust, W.M. 1989. Abiotic functional changes of a water tupelo- baldcypress wetland following disturbance by harvesting. Raleigh, NC: North Carolina State University, Department of Forestry, 196 p. Ph.D. dissertation.

Aust, W.M.; Lea, R. 1992. Comparative effects of aerial and ground logging on soil properties in a tupelo-cypress wetland. Forest Ecology and Management. 50:57-73.

Aust, W.M.; Lea, R. 1991. Site temperature and organic matter in a disturbed forested wetland. Soil Science Society of America Journal. 55(6):1741-1746.

Aust, W.M.; Lea, R.; Gregory, J.D. 1991. Removal of floodwater sediments by a clearcut tupelo-cypress wetland. Water Resources Bulletin. 27(1):111-116.

Aust, W.M.; Schoenholtz, S.H.; Zaebst, T.W., Szabo, B.A. 1997. Recovery status of a tupelo-cypress wetland seven years after disturbance: silvicultural implications. Forest Ecology and Management. 90:161-167.

Conner, W.H. 1994. Effects of forest management practices on southern forested wetland productivity. Wetlands. 14(1):27-40.

Ewel, K.C. 1996. Sprouting by pondcypress (*Taxodium distichum* var. *nutans*) after logging. Southern Journal of Applied Forestry. 20(4):209-213.

Kennedy, H.E. 1982. Growth and survival of water tupelo coppice regeneration after six growing seasons. Southern Journal of Applied Forestry. 6:133-135.

Krinard, R.M. 1980. Black willow. In: Eyre, F.H., ed. Forest cover types of the United States and Canada. Washington, DC: Society of American Foresters: 66.

Larsen, H.S. 1980. Baldcypress-tupelo. In: Eyre, F.H., ed. Forest cover types of the United States and Canada. Washington, DC: Society of American Foresters: 68.

Lockaby, B.G.; Stanturf, J.A.; Messina, M.G. 1997. Effects of silvicultural activity on ecological processes in floodplain forests of the Southern United States: a review of existing reports. Forest Ecology and Management. 90(2,3):93-100.

Mader, S.F. 1990. Recovery of ecosystem functions and plant community structure by a tupelo-cypress wetland following timber harvesting. Raleigh, NC: North Carolina State University, Department of Forestry. 288 p. Ph. D. dissertation.

Mader, S.F.; Aust, W.M., Lea, R. 1989. Changes in functional values of a forested wetland following timber harvesting practices. In: Hook, D.D.; Lea, R., eds., Forested wetlands of the Southern U.S. Gen. Tech. Rep. SE-50. Asheville, NC: U.S. Department of Agriculture: 149-154.

Meadows, J.S.; Stanturf, J.A. 1997. Silvicultural systems for southern bottomland hardwood forests. Forest Ecology and Management. 90(2,3):127-140.

Powell, S.W.; Day, F.P., Jr. 1991. Root production in four communities in the Great Dismal Swamp. American Journal of Botany. 78(2):288-297.

Steel, R.G.D.; Torrie, J.H. 1980. Principles and procedures of statistics: A biometrical approach. 2nd ed. New York: McGraw- Hill Book Company. 633 p.

Szabo, B.A.; Schoenholtz, S.H.; Aust, W.M. 1994. Long-term effects of timber harvesting on soil redox potential and pH in a baldcypress-tupelo wetland. Abstracts, third Symposium on the biogeochemistry of wetlands; 1994 June 26-29; Orlando, FL: 46.

U.S. Army Corps of Engineers. 1987. River stages from the Barry Steam Plant, 1985-1996. Mobile Distirct.

USDA Natural Resources Conservation Service. 1997. Official soil series description, Levy series.

Walbridge, M.R. 1993. Functions and values of forested wetlands in the Southern United States. Journal of Forestry. 91(5):15-19.

Zaebst, T.W. 1997. Recovery status of a cypress (*Taxodium distichum*) - water tupelo (*Nyssa aquatica*) wetland seven years after harvest disturbance. Blacksburg, VA: Virginia Polytechnic Institute and State University, Department of Forestry. 172 p. M.S. Thesis.

INTERACTION AMONG MACHINE TRAFFIC, SOIL PHYSICAL PROPERTIES AND LOBLOLLY PINE ROOT PROLIFERATION IN A PIEDMONT SOIL

Emily A. Carter and Timothy P. McDonald[1]

Abstract—The impact of forwarder traffic on soil physical properties was evaluated on a Gwinnett sandy loam, a commonly found soil of the Piedmont. Soil strength and saturated hydraulic conductivity were significantly altered by forwarder traffic, but reductions in air-filled porosity also occurred. Bulk density did not increase significantly in trafficked treatments. The greatest impacts to soil physical properties occurred in the surface layer. Loblolly pine root proliferation increased in both trafficked and untrafficked treatments but differed in the soil depth at which this occurred. Further investigations are necessary to understand the response of roots to machine traffic.

INTRODUCTION

The impact of forest machinery on harvested sites traditionally has been gauged by changes in soil physical properties including bulk density, soil strength, macroporosity, saturated hydraulic conductivity, and water infiltration (Gent and Ballard 1984, Greacen and Sands 1980, Lenhard 1986, Reisinger and others 1988, Wronski 1984). Soil physical properties are negatively impacted during trafficking; the results can persist for many years and limit tree productivity (Greacen and Sands 1980, Tuttle and others 1988). Low productivity of selected pine species is correlated with impaired root growth and development in compacted soils. Compaction restricts the volume of soil that can be exploited for available moisture and nutrients (Mitchell and others 1982, Sands and Bowen 1978, Tuttle and others 1988). The relationship among machinery, root systems, and soil physical properties has been extensively investigated in agricultural systems and linked to numerical values of soil physical properties that are considered to be root limiting (Unger and Kaspar 1994). An understanding of this relationship for tree species is limited, and future productivity would be aided by an understanding of soil physical changes and their role in root growth.

The objective of the study was an evaluation of the impact of forwarder traffic on selected soil physical properties of a Piedmont soil, and determination of a response by loblolly pine roots to forwarder traffic.

METHODS

The study was established in June 1996 on experimental sites managed by the School of Forestry, Auburn University, and cultivated for agricultural use prior to its conversion to a loblolly pine (*Pinus taeda*) stand. The study site supported a 15-year-old loblolly pine stand with an average diameter at breast height (d.b.h.) of 21 centimeters in a 2.7- by 1.8-meter spacing. The soil series within the study site was identified as a Gwinnett sandy loam, a member of the clayey, kaolinitic, thermic family of Typic Rhodudults. The experimental design consisted of a randomized complete block with two treatments: untrafficked (UNT) and trafficked by a loaded forwarder (TR), and replicated twice. Each replication encompassed an area approximately 3,700 square meters, subdivided into two treatment areas each approximately 1,350 square meters in size and separated by a buffer strip measuring approximately 9 by 45 meters. Each treatment plot contained approximately 12 rows of loblolly pines with 15 trees per row.

Pretreatment site preparation was necessary to permit movement of the forwarder through the stand. This consisted of hand-felling every other row of trees, limbing and topping of trees on site, winching boles to the edge of each treatment block, and removal from treatment areas. Similar pretreatment site preparation was applied to the UNT treatment areas to ensure uniform site conditions for consistency in comparisons. Trafficked treatments consisted of 10 passes of a loaded Franklin 710 forwarder weighing approximately 13 tons and driven at a rate of 3 miles per hour after removal of slash from traffic lanes.

Soil sampling was conducted in three phases: (1) bulk soil sample collection in June 1996 after pretreatment site preparation; (2) collection of soil core after pretreatment and again after installation of traffic treatments in June 1996 in one replication to assess impact of traffic; and (3) collection of soil cores in fall 1996 from each treatment in both replications to compare soil physical properties of UNT and TR treatments. Bulk soil samples were collected at 12 locations in each block with a hand-held auger, in increments of 15 centimeters to a depth of 90 centimeters. The samples were then air-dried, ground, and passed through a 2 millimeter sieve for soil chemical and physical analyses. Sixteen soil cores, 5 centimeters in diameter and 5 centimeters in length, were collected from the soil surface layer (0 to 10 centimeters) at random locations along traffic lanes in one replication of TR prior to and at the conclusion of traffic treatments. Soil cores of similar dimension were collected along traffic lanes at regular intervals (approximately 10 meters) in UNT and TR in each replication to compare treatments; the number of cores collected was dependent on the type of soil physical analysis and the number of soil depths.

Bulk soil samples were analyzed for particle size by the hydrometer method according to Klute (1986). Soil cores

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collected from pre- and post-traffic treatments were analyzed for bulk density, gravimetric water content; saturated hydraulic conductivity; soil moisture retention characteristics at potentials of -1/10, -1/3, -1, and -5 bar; and porosity (total and microporosity) according to Klute (1986). Air-filled porosity was measured in each core according to Carter (1990). A total of 72 soil cores was collected from the UNT and TR treatment areas of each replication from three locations per track (or row) at three depths: 0 to 10, 10 to 20, and 20 to 30 centimeters. The cores were analyzed for bulk density and gravimetric water content according to methods previously cited. Additional cores were collected in each row at one location in each treatment, at two depths (0 to 10 and 10 to 20 centimeters) for a total of 20 soil cores per replication. These were analyzed for saturated hydraulic conductivity, soil moisture retention characteristics, and air-filled porosity.

Soil strength was determined with a Rimik CP 20 cone penetrometer with a base cone diameter of 113 square millimeters, manually inserted to a depth of 300 millimeters, and recorded in 25 millimeter increments. Soil strength is expressed indirectly as cone index (CI), or the force required divided by the cross-sectional area of the base of the cone and measured in units of pressure (megapascals). Soil strength is reported for fall 1996 only.

Root samples were collected prior to installation of traffic treatments in June 1996 and in traffic lanes in fall 1996. Root samples were collected in June 1996 by manually driving polyvinyl chloride (PVC) cores, 7.6 centimeters in diameter and 60 centimeters in length, in 12 random locations in each block. The PVC cores were removed, subdivided into 10 centimeter increments, and roots and soil separated in a Gillison Root Washer. Root length (centimeters) was estimated utilizing a Comair Root Length Scanner and root length densities were calculated by dividing total root length (centimeters) by soil core volume (cubic centimeters). Root length densities were estimated for trafficked and untrafficked sites in one block in Fall 1996 through the collection of five soil cores, 5 centimeters in diameter and 30 centimeters in length, as a transect across one traffic lane (outside track, in track, and between tracks) in three locations along the length of one traffic lane; a total of 15 cores per treatment was collected. Preparation of root samples and root length density calculations were performed as previously described.

Statistical analyses were performed utilizing the Statistical Analysis System (SAS) (SAS 1988). Data collected for soil physical properties were analyzed in an analysis of variance (ANOVA), and means were analyzed by paired t tests. Comparisons of soil physical data from pre- and post-traffic sites was performed by paired t tests.

RESULTS AND DISCUSSION

Soil Physical Characterization

Soil texture and bulk density of the study site are typical for soils of the Piedmont physiographic region (tables 1 and 2). Particle size analysis indicated the presence of subsoil layers with a high percentage of clay. This is indicative of the presence of an argillic horizon (B2t), a defining characteristic of the Ultisol soil order of which the Gwinnett soil series is a member. Bulk density values of 1.3 megagrams per cubic meter of the surface soil layer were higher than expected for forest soils of the Piedmont. The high soil porosity, both total and air-filled, high hydraulic conductivity, and low percentage of gravimetric water content at field capacity (-1/10 bar) is a consequence of the sandy nature of the surface soil layer and the positive influence of undisturbed tree growth (table 1 and fig. 1).

Soil physical characteristics determined for soil samples of the study site are similar to properties reported for a Gwinnett sandy loam (SCS 1981). The Gwinnett soil series is a highly weathered, Piedmont soil of low moisture capacity in surface horizons underlain by a B2t, or argillic, subsoil horizon. Bulk density reported for an undisturbed Piedmont forest soil was 1.16 megagrams per cubic meter

Table 1—Impact of forwarder traffic on selected soil physical properties of a Gwinnett sandy loam soil

	Physical Property					
				Porosity		
Soil status	Bulk density	Moisture content	Saturated hydraulic conductivity[a]	Air-filled	Microporosity	Total
	Mg/m^{-3}	*Percent*	--------*Cm/hr^{-1}*--------	------------------*Percent*------------------		
Pretraffic	1.30	21.4	2.43	32.5	20.3	52.7
Posttraffic	1.56	19.7	0.177	22.7	18.4	41.2

[a] Means of soil physical parameters were significantly different at the P = 0.05 level.

Table 2—Particle size analysis of a Gwinnett sandy loam soil

Depth	Sand	Silt	Clay	Classification
----Cm----	-------Percent-------			
0 - 10	72	6	23	Sandy clay loam
10 - 20	47	18	35	Sandy clay
20 - 35	30	28	43	Clay
35 - 45	30	25	43	Clay

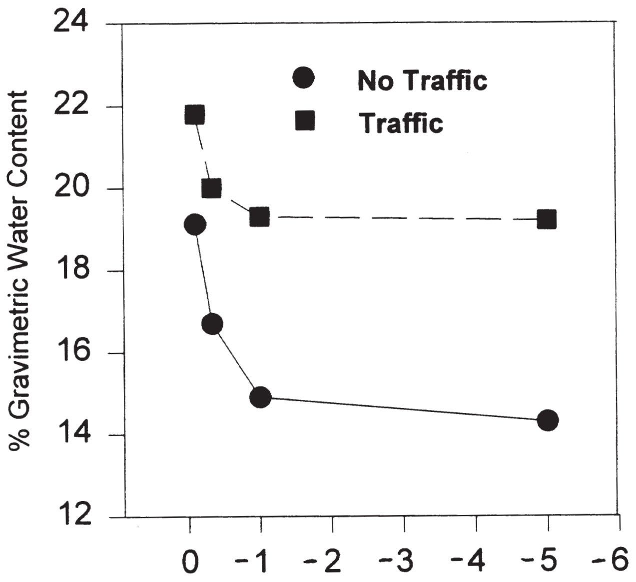

Figure 1—Soil moisture retention characteristics of the surface layer of a Gwinnett sandy loam subjected to no traffic (UNT) and traffic (TR).

(Gent and Ballard 1984). In spite of elevated bulk density values, saturated hydraulic conductivity of 2.34 centimeters per hour and macroporosity in the vicinity of 33 percent are typical of forest soils that remain undisturbed for extended periods of time (Reisinger and others 1988).

Impact of Forwarder Traffic

Bulk density, soil moisture retention, hydraulic conductivity, and porosity of the soil surface layer responded negatively to forwarder traffic (table 1 and fig. 1). Soil compaction as a result of forwarder traffic increased in the study site as indicated by increased bulk density and decreased air-filled porosity. Total porosity was reduced at the expense of the large, air-filled pores in the surface layers after trafficking, which converted soil macropores to micropores. This change in pore size reduced the ability of the soil to transmit water and increased the soil moisture retention rate at each soil moisture potential. An indication of the alteration of pore size from trafficking is the shift in moisture retention characteristics in TR compared to UNT (fig. 1).

The changes in soil physical properties reported in this study are typical of the impact of machine traffic on bulk density, macroporosity, and saturated hydraulic conductivity of forest soils (Incerti and others 1987, Lenhard 1986, Wronski 1984). Bulk density increased to 1.56 megagrams per cubic meter in the surface layer of TR, matching bulk density values reported for heavily trafficked (in skid trails) sandy loam soils in North Carolina (Gent and others 1984). Air-filled porosity decreased from 33 to 23 percent in traffic lanes but the post-traffic air-filled porosity of 22 percent exceeds the minimum air filled percentage of 10, which is considered to be the lower limit for proper oxygen diffusion (Incerti and others 1987). Saturated hydraulic conductivity reductions from 2.34 to 0.177 centimeters per hour were typical of sandy loam (or finer) soils subject to compaction (Akram and Kemper 1979).

Subsoil Response to Forwarder Traffic

Soil response to forwarder traffic was detectable in subsurface (greater than 10 centimeters) as well as surface (0 to 10 centimeters) layers (table 3 and fig. 2). Bulk density was lower in UNT compared to TR at comparable depths, and may indicate a response, however slight, to forwarder traffic. An ANOVA determined that neither the treatment, the depth, nor their interaction was significant for bulk density. Cone index (CI) values were consistently and significantly higher in TR than in UNT at all sampled depths ($P > 0.001$). Although significant differences were detected at every depth, the impacts associated with trafficking may be limited to the upper 15 centimeters where the greatest differences occurred. A 10 percent difference in air-filled porosity and a tenfold reduction in saturated hydraulic conductivity were detected between TR and UNT in the surface layer, and little difference was discerned in the

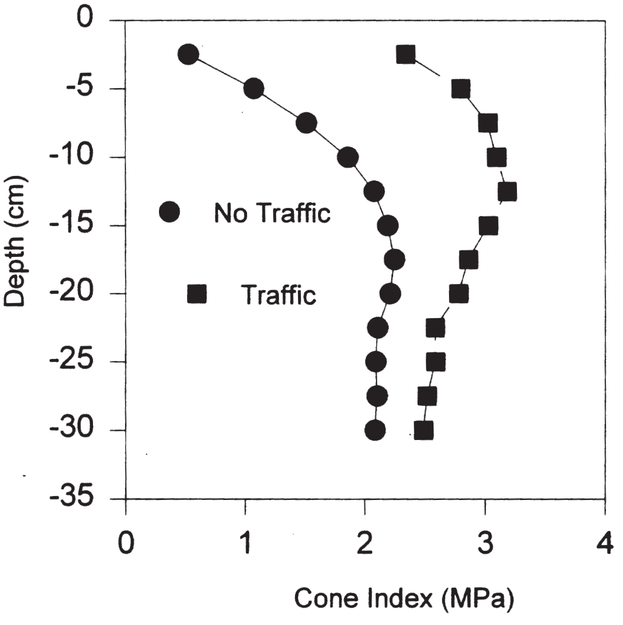

Figure 2—Cone index (MPa) measurements of a Gwinnett sandy loam subjected to no traffic (UNT) and traffic (TR). All depths are significantly different between treatments ($P > 0.001$).

Table 3—Comparison of soil physical properties at selected depths of a Gwinnett sandy loam subjected to two levels of trafficking

Treatment	Bulk density	Gravimetric water content	Air-filled porosity	Saturated conductivity
	Mg/m^{-3}	--------------*Percent*---------------		*Cm/hr^{-1}*
Traffic				
0 - 10	1.57	21.0	27.7	0.27
10 - 20	1.70	15.2	21.1	0.186
20 - 30	1.77	17.4	ND	ND
No Traffic				
0 - 10	1.51	22.1	37.3	3.12
10 - 20	1.69	16.5	18.7	0.078
20 - 30	1.66	18.9	ND	ND

ND = no samples analyzed.

subsoil layer. Treatment alone did not significantly affect air-filled porosity but was significantly lower in subsoil layers than in surface layers. Saturated hydraulic conductivity of TR slightly exceeded UNT in the 10 to 20 centimeter layer and is potentially explained by the higher porosity of this layer. Treatment, depth, and their interaction were significant sources of variation for saturated hydraulic conductivity. Saturated hydraulic conductivity in surface layers was significantly higher than in subsoil layers for both treatments, and conductivity was reduced significantly in the surface layer in trafficked soils.

Natural differences in soil physical properties between surface and subsurface layers may be present in highly weathered soils and potentially explained in terms of soil texture. Bulk density and soil strength increases with depth, under undisturbed conditions (UNT), occurred simultaneously with clay content increases and sand fraction decreases. Bulk density and soil strength are known to vary under the influence of particle size distributions in a soil layer (Carter 1990, Tuttle and others 1988). The presence of clay and very fine sand correlated well with higher bulk density and soil strength values in undisturbed profiles in North Carolina (Vepraskas 1988).

Machine traffic exacerbates natural conditions by packing soil particles closer together regardless of texture, and increasing bulk density and soil strength at the expense of porosity (Greacen and Sands 1980). The impact of such activities is often limited to the near-surface soil environment, although changes in soil properties can be induced below 40 centimeters by increasing loads (Burger and others 1985, Greacen and Sands 1980). Soil strength data may corroborate this observation as the extent of impact from machine traffic was greatest in the upper 15 centimeters. Significant differences in CI between treatments at every depth may reflect the influence of varying moisture conditions at the time of measurement. Cone index was determined in one replication under low moisture conditions rather than field capacity, which is necessary to minimize the influence of related soil factors on penetration resistance (O'Sullivan and others 1987). This may have overestimated soil strength when CI values were averaged for each treatment.

Loblolly Pine Root Proliferation

Root length proliferation within the soil profile was highest in the surface layer and tapered with depth. Root length densities were less than 4 centimeters per cubic centimeter at each depth interval, with a high standard deviation (table 4). The high standard deviations indicate a high degree of variability for root densities, which is typical of this type of data. Root proliferation increased in trafficked treatments (UNT vs. TR) from the pretraffic levels and appeared to be influenced by forwarder traffic. However, significant increase in root biomass in UNT also occurred. Regardless of the reason for these differences, total root biomass accumulation in the sampled profile in UNT and TR were similar, but distribution differences were evident. The

Table 4—Root length densities and standard deviations of a 15-year-old loblolly pine stand under pretraffic and trafficked conditions in a Gwinnett sandy loam

	Root length density		
		Posttraffic	
Depth	Pretraffic	Traffic	No traffic
Cm	----------------------*Cm/cm^{-3}*	----------------------	
0 - 10	3.72 (1.58)	17.87 (9.46)	6.39 (0.66)
10 - 20	1.99 (1.52)	3.57 (2.13)	20.07 (21.46)
20 - 30	1.72 (0.76)	2.50 (1.54)	1.92 (0.09)

majority of root mass accumulation in UNT occurred in the intermediate depth of 10 to 20 centimeters as opposed to TR, which experienced root proliferation in the surface layer.

Root length distribution under undisturbed conditions (pretreatment) was similar to root distributions reported for *Pinus elliottii* Engelm. and *P. radiata* (Davis and others 1983, Escamilla and others 1991). The natural decline in root length density with depth may reflect subsoil conditions that limited root growth and proliferation. The limited number of studies on the influence of soil physical properties on pine root growth have found root growth to be limited at bulk densities of 1.4 and 1.6 megagrams per cubic meter in a sandy clay loam and sandy soil, respectively, and at cone index values in excess of 3.0 MPa (Sands and Bowen 1978, Sands and others 1979, Tuttle and others 1988). Root response after trafficking may be the result of soil physical properties that changed in surface layers. This may have induced a large degree of proliferation due to its inability to penetrate below 10 centimeters. A similar situation had the potential to occur in UNT as naturally occurring limits were encountered at the 20 centimeter depth. The impact of traffic on root proliferation requires more indepth evaluation.

CONCLUSION

Forwarder traffic had a negative impact on the soil physical properties of a Gwinnett sandy loam. Significant changes occurred in soil strength and saturated hydraulic conductivity as a result of forwarder traffic. The impacts were greatest in the surface layer and, to a lesser degree, in subsoil layers. Root distribution within undisturbed profiles was relatively uniform but forwarder traffic appeared to induce root proliferation. The change in soil properties was consistent with other studies but root performance in trafficked plots did not agree with results reported by others.

LITERATURE CITED

Akram, M.; Kemper, W.D. 1979. Infiltration of soils as affected by the pressure and water content at the time of compaction. Soil Science Society of America Journal. 43:1080-1086.

Burger, J.A.; Perumpal, R.E.; Kreh, R.E.; [and others]. 1985. Impact of tracked and rubber tired tractors on a forest soil. Transactions of the American Society of Agricultural Engineers. 28:369-373.

Carter, M.R. 1990. Relationship of strength properties to bulk density and macroporosity in cultivated loamy sand to loam soils. Soil and Tillage Research. 15:257-268.

Carter, M.R., ed. 1990. Soil sampling and methods of analysis. Canadian Society of Soil Science. Boca Raton, FL: Lewis Publishers: 823.

Davis, G.R.; Neilsen, W.A.; McDavitt, J.G. 1983. Root distribution of *Pinus radiata* related to soil characteristics in five Tasmanian soils. Australian Journal of Soil Research. 21:165-171.

Escamilla, J.A.; Comerford, N.B.; Neary, D.G. 1991. Soil-core break method to estimate pine root distribution. Soil Science Society of America Journal. 55:1722-1726.

Gent, J.A., Jr.; Ballard, R. 1984. Impact of intensive forest management practices on the bulk density of lower Coastal Plain and Piedmont soils. Southern Journal of Applied Forestry. 9:44-48.

Greacen, E.L.; Sands, R. 1980. Compaction of forest soils. A review. Australian Journal of Soil Research. 18:163-189.

Incerti, M.; Clinnick, P.F.; Willatt, S.T. 1987. Changes in the physical properties of a forest soil following logging. Australian Forest Resources. 17:91-98.

Klute, A., ed. 1986. Methods of soil analysis: Part 1. Physical and mineralogical methods. 2nd ed. Madison, Wisconsin: American Society of Agronomy: 1188.

Lenhard, R.J. 1986. Changes in void distribution and volume during compaction of a forest soil. Soil Science Society of America Journal. 50:462-464.

Mitchell, M.L.; Hassan, A.E.; Davey, C.B.; Gregory, J.D. 1982. Loblolly pine growth in compacted greenhouse soils. Transactions of the American Society of Agricultural Engineers. 25:304-307.

O'Sullivan, M.F.; Dickson, J.W.; Campbell, D.J. 1987. Interpretation and presentation of cone resistance data in tillage and traffic studies. Journal of Soil Science. 38:137-148.

Reisinger, T.W.; Simmons. G.L.; Pope, P.E. 1988. The impact of timber harvesting on soil properties and seedling growth in the South. Southern Journal of Applied Forestry. 12:58-66.

Sands, R.; Bowen, G.D. 1978. Compaction of sandy soils in radiata pine forests. II. Effects of compaction on root configuration and growth of radiata pine seedlings. Australian Journal of Forest Research. 8:163-170.

Sands, R.; Greacen, E.L.; Gerard, C.J. 1979. Compaction of sandy soils in radiata pine forests. I. A penetrometer study. Australian Journal of Soil Research. 17:101-113.

Soil Conservation Service. 1981. Soil survey of Lee County, Alabama. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service: 100.

Tuttle, C.L.; Golden, M.S.; Meldahl, R.S. 1988. Soil compaction effects on *Pinus taeda* establishment from seed and early growth. Canadian Journal of Forest Research. 18:628-632.

Unger, P.W.; Kaspar, T.C. 1994. Soil compaction and root growth: a review. Agronomy Journal. 86:759-766.

Vepraskas, M.J. 1988. Bulk density values diagnostic of restricted root growth in coarse-textured soils. Soil Science Society of America Journal. 52:1117-1124.

Wronski, E.B. 1984. Impact of tractor thinning operations on soils and tree roots in a Karri Forest, Western Australia. Australian Forest Research. 14:319-332.

LOW COST FOREST OPERATION SYSTEMS FOR MIXED SPECIES MANAGEMENT

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Abstract–This is a summary paper about the development of forest operation systems for regenerating mixed pine and hardwood stands that reduce costs and environmental impacts by working more in concert with natural successional trends. The environmental impacts focus on protecting site productivity, primarily through reducing the impacts of forest operations on post-harvest soil movement. The cost savings result from not spending resources on trying to eradicate the hardwood component that develops naturally over time on these kinds of sites. The primary operations involve clearcutting the merchantable stand, felling the residual trees, implementing post-harvest site preparation burns, and planting pine seedlings at wide spacings among the hardwood regrowth. Timing of the residual felling affects fuel structure and subsequent intensity and uniformity of the post-harvest fire. A key step in protecting against excessive soil movement is to not consume the forest floor with the fire. As forest floor is reduced, soil movement increases. Timing of the residual felling also affects post-harvest fire behavior, early vegetative development of the hardwood regeneration, and small mammal population dynamics. We have results from a preliminary investigation into the interrelations that forest operations have with landform and edaphic properties of site. It links vegetative response to land units defined and delimited by an ecological classification system. This classification system uses landform and edaphic variables to predict the range of seral plant-community development to expect on a particular parcel of land. Preliminary results from a case study show how ecological units can respond differently when treated similarly.

INTRODUCTION

Seventy-five percent of the forest land base in the Piedmont region of the Southern United States is controlled by nonindustrial private forest (NIPF) landowners. The NIPF land base is large, but individual holdings are on the average small, which means that the number of landowners is large. The landholders own land for many different reasons, so it stands to reason that they have widely varying land-use objectives. A major disincentive for these landowners to practice good forest management is low unit value for stumpage due to an overabundance of low-quality timber and the risks associated with the long-term nature of forestry investments. The consequence of these disincentives is a harvest-only management approach that removes marketable trees and leaves behind low-quality residual trees. The larger, low-quality residual trees disproportionately capture the site because of their size advantage relative to the regeneration that results from the harvest activities. This produces a negatively reinforcing cycle of increasingly poor-quality trees, and further erosion of the incentive for investing in higher future timber yields.

Industrial assistance programs for NIPF landowners, and government supported cost-share incentives have helped put some of these lands into productive pine plantations, but this effort is small relative to the magnitude of the problem. Furthermore, the objectives of pine plantation management are often too narrow for NIPF landowners, and the public incentive dollars used to create the plantations are becoming increasingly difficult to justify as tax dollar expenditures. Pine plantation establishment procedures are designed to reduce or temporarily eliminate the hardwood component that develops naturally in Piedmont stands, but these kinds of activities extract a high cost in terms of energy used and productivity lost through soil disturbance and nutrient loss from the site. The end result of these constraints is that a high percentage of the 21 million-acre NIPF land base is being stocked with timber of low quality and/or lower than optimal density.

The guiding hypothesis for our overall research program has been that low-quality, mixed-species stands like those developing naturally on much of the NIPF land base can be cost-effectively managed for improved timber production as mixed southern yellow pine and hardwood stands. Naturally regenerated, largely low-quality, mixtures of pines and hardwoods are presently found on about one quarter (or about 7.1 million acres) of the total Piedmont commercial forest. This research has focused on how understanding the disturbance patterns and post-disturbance species composition responses that produce these pine-hardwood stands can be used to develop forest operation systems that work with nature. The result is operations that produce good-quality, well-stocked, pine-hardwood mixtures at less investment cost, with less impact to the site, and which meet a wider range of land management objectives than does the proven pine plantation system.

This paper does not report the results from a single study, with the usual detailed descriptions of the experimental design, methods, and results. Rather, it summarizes most of the literature that the USDA Forest Service and other research institutions have reported about pine-hardwood regeneration dynamics in the Piedmont physiographic region, and the implications these biological responses have on forest operation systems. The first group of studies deals with quantifying the effects of several forest operation scenarios on pine-hardwood regeneration dynamics and site productivity. We conclude by examining what a case study has to suggest about the potential role of ecological land classification on forest operation prescriptions, or specifically: how ecological units can be used to relate

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vegetative response to forest operations using spatial measures of landform and soil attributes.

FOREST OPERATIONS FOR ESTABLISHING PINE-HARDWOOD MIXTURES

The rapid initial height growth of hardwood coppice relative to pines from seed or planted seedlings has been a source of concern to managers and researchers interested in establishing pine when hardwood competition is not controlled. As a result, initial research emphasis was on cost-effective means of controlling hardwood regeneration long enough to allow the shade-intolerant pines to become established as a component of the overstory canopy. McGee (1986, 1989) reported high survival and rapid growth of planted loblolly pines (*Pinus taeda* L.) after harvesting low-quality hardwood stands by chainsaw to a 4-inch lower diameter limit (with and without herbicide injection of residuals) and by shearing to a 1-inch limit. Lloyd and others (1991) showed for the Appalachian foothills region of South Carolina that diameter growth of shortleaf pines (*P. echinata* Mill.) in pine-hardwood mixtures improved after release at age 4, but that release was not necessary to assure survival. In a study by McMinn (1989), naturally regenerated shortleaf, virginia (*P. virginiana* Mill.), and loblolly pines were largely absent from areas harvested in the growing season and were suppressed in dormant-season commercial clearcuts that left large (relative to regeneration) residual trees.

Much of our research on hardwood control has centered on a set of operations described by Abercrombie and Sims (1986) which proved successful in the Southern Appalachian Mountains (Phillips and Abercrombie 1987). The technique includes a commercial clearcut followed by spring felling of residual hardwood stems (> 2 meters in height) and a summer broadcast burn. Felling and burning are designed to control hardwood sprout growth so pines can be established without eliminating hardwoods. Pines are planted the following winter at a wide spacing (15 by 15 feet or more) to reduce costs and to avoid early canopy closure of the pines over the hardwood, thus insuring that some hardwoods will receive direct light from above, and thus contribute significantly to merchantable stand growth.

Site preparation burning is an attractive operation for pine-hardwood regeneration in the mountains for several reasons. Burning is less expensive than mechanical site preparation and, if done properly, has less environmental impact. By burning in July, as suggested by Abercrombie and Sims (1986), hardwood sprouts are top-killed and new sprouts that emerge after burning have a shortened growing season. These new sprouts remain shorter than sprouts in unburned stands for 4 years or more, allowing pines a better chance to survive (Waldrop 1995). Sprout quality is improved by burning because stump sprouts are replaced by well-anchored basal or root sprouts (Augspurger and others 1989). Site preparation burning proved to be particularly attractive in areas with heavy coverage of mountain laurel (*Kalmia latifolia* L.) that would be too expensive to regenerate using mechanical control (Williams and Waldrop 1995).

Early trials of pine-hardwood regeneration in the Piedmont suggested that site preparation burning might be too risky (Waldrop and others 1989). In this region, forest floor thickness varies by site, but remains substantially thinner than in the mountains (Ball and others 1993). Therefore, the danger of exposing soil to erosion by consuming the forest floor organic layer is much greater in the Piedmont. For example, Van Lear and Kapeluck (1989) reported the loss of over 1.5 inches of topsoil during a 9-month period after burning a Piedmont site that had been subjected to an extended dry period prior to the rain event that prompted the burn. Other than the weather conditions prior to the burns, the burning prescription used in that study was identical to one used in a previous study in the Appalachian foothills region in South Carolina (Van Lear and Danielovich 1988) where burning caused no increase in erosion. In this Piedmont experiment, the rainfall events that prompted the burn were insufficient to break the preceding drought, thus allowing the fire to totally consume the forest floor. This, coupled with the thinner organic layer characteristic of the Piedmont, resulted in damaging results.

Several studies are being conducted to learn how to use site preparation burning without causing erosion. Robichaud and Waldrop (1994) burned adjacent mountain sites using burning prescriptions that created conditions of low- and high-severity fire impacts (with regard to soil exposure). Low-severity burns were conducted 6 days after a 4-day rainfall event totaling 1.5 inches. For this burn, the moisture content of the litter layer was 65.2 percent. High-severity burns were conducted 14 days after a rainfall of 1.7 inches and with the moisture content of the litter layer at only 5.9 percent. Sediment loss for one year after burning totaled 2.33 tons per acre from the high-severity burns, but only 0.06 tons per acre from the low-severity burn (Stone and others 1995). Site productivity was reduced by high-severity burning with biomass production being two times greater in the low-severity sites (0.32 vs. 0.68 tons per acre). Even though high-severity burning reduced site quality, pine survival was significantly higher in the high-severity burn areas (77 percent in the high-severity area versus 58 percent in the low-severity). This result was attributed to increased vegetative competition on the low-severity sites.

Fire severity is also related to another operation used to establish pine-hardwood mixtures: the felling of residual hardwood stems. Residual stems are supposed to be felled by chainsaw crews during the spring when new leaves are almost fully developed. Broadcast burns are conducted 4 to 6 weeks after the stems are felled, generally in mid-July to early August. By that time, the fine woody fuels are dried sufficiently to burn intensely. Waldrop (1995) showed how fire behavior and fire severity is controllable by varying the season of the residual-stem felling. By felling during winter, foliage was not present. Therefore, the easily ignited leaf litter was limited to that found on the forest floor, and if burning conditions are as they should be, this material will be relatively moist and will not burn well, thus making it difficult to get the fire to carry between areas of accumulated slash. In spring-felled areas, dry leaves left on the felled residuals carried the fire, producing uniform burns across the entire study area, while winter felling produced a patchy burn pattern. The patchy burns for the winter felling operation may help meet some objectives by increasing early-successional plant and animal species diversity (Evans and others 1991) and contributing to early stand structural diversity by leaving more woody debris. Also, winter felling may reduce erosion by decreasing burn severity and leaving more debris dams; however, this effect has not been studied.

Even though winter felling may reduce erosion, it may not control hardwood competition as well as felling in spring. Phillips and Abercrombie (1987) suggested that spring felling would better control hardwood sprout growth than winter felling because spring felling is conducted when carbohydrate reserves in root systems have been exhausted by the early season growth initiation. Geisinger and others (1989) found that hardwood sprouts in the Piedmont region were shorter in spring-felled areas than in winter-felled areas after one growing season. However, by the end of six growing seasons the winter felling of residual stems, followed by a summer site preparation burn, had produced nearly identical stands to those regenerated by spring felling and summer burning (Waldrop 1997). Growth reductions from spring felling lasted only one growing season and had no apparent effect on stand development. This result suggests that the precise timing of felling as described by Phillips and Abercrombie (1986) is not as critical for the Piedmont ecosystem.

Several studies of regeneration techniques in the Piedmont suggest that little or no site preparation is needed to establish pine-hardwood mixtures on the medium-to-dry sites. Waldrop (1991) and Perry and Waldrop (1993) report on a study that harvested small groups in 0.10- and 0.33-acre openings, in a merchantable-sized hardwood stand, with the long-term goal of creating multi-aged, pine-hardwood stands. They found that edge trees reduced hardwood height growth in the opening more than that of planted loblolly pines. This pattern allowed the pines to overtop hardwoods within 2 years with no site preparation. In another study involving clearcutting the entire stand, Waldrop (1997) found that site preparation burning did not improve the survival or growth of planted loblolly pines. Pines overtopped hardwoods in burned areas by age 4 and in unburned areas by age 6 (fig. 1).

We know that hardwood regeneration is more abundant and faster growing on high productivity sites, so crown closure could occur on these better sites before pines reach the upper canopy. Additional research is needed to identify the kinds of sites where forest operation systems designed to regenerate pine-hardwood mixtures will work. Ecological land classification might have a role to play in improving these kinds of decisions.

USING ECOLOGICAL CLASSIFICATION IN PLANNING FOREST OPERATIONS

Pine-hardwood regeneration research in the Piedmont physiographic region has focused so far on the dryer-than-

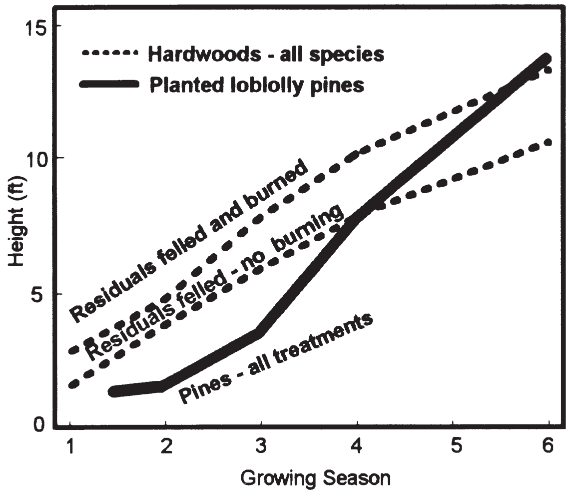

Figure 1—Mean height of natural hardwood regeneration (by site preparation treatment) and planted loblolly pines (all treatments combined) for 6 years after harvest.

average sites. These results on dry sites suggest that little more than felling the non-merchantable residuals and planting pine with wide spacing is needed to get a productive pine-hardwood mixture. However, it is well known that hardwood coppice and advanced seedling regeneration will outgrow pine seedlings on the better sites. In the upland forest of the Piedmont region, an important productivity gradient is due to increasing soil moisture availability. Hardwoods are not only more sensitive to site productivity than pines, but they are also more abundant on the better sites. If we had a practical way to model moisture gradients, we might be able to tailor harvesting prescriptions to site conditions. Jones (1991) has developed a promising model of land classification for the Piedmont region that appears to capture a meaningful ecological gradient that has potential for helping tailor forest operation prescriptions.

A lot of soil-site research has tried, with very limited success, to develop predictor equations of site productivity using only a few key variables. Jones' (1991) approach recognizes the inherent difficulty in identifying a few predictor variables that will reliably quantify an ecologically meaningful gradient. In most cases, the gradients to which plants respond are very complex, involving the interplay of numerous variables, many of which we do not even know about. His approach is to let the plants do the integration of variables for us through the patterns of species birth, growth, and death that produce the range of plant communities we find developing on a site over time. Specifically, he investigates the presence and absence of plant species on reference sites, where reference sites are areas that have no signs of major species-eradicating disturbances. Classification methods are used to organize and present the results through the use of the relationship that species presence and absence has with spatially oriented landform, and edaphic variables. The spatial (or map oriented) nature of the landform and edaphic variables are then used to identify and delimit ecologically equivalent land units.

These spatially explicit, vegetation-derived, landform/ edaphic relationships are then used to delimit land units independent of vegetative cover presently on the land. This approach provides a way to sort out and categorize the wide array of seral communities that can occur across an entire region. The hypothesis is that the range of seral community development within ecological classes will be less than the range of seral communities encountered across all site units. This approach has provided an easy-to-use land classification format useful in organizing what experienced foresters learn intuitively from field observations about site and plant community relationships. We see potential for using the ecological classification to predict species compositional dynamics that follow specific forest operations on specific land units.

Although the pine-hardwood regeneration study reported by Waldrop (1997) was not designed to investigate the potential of Jones' model in aiding forest operation prescriptions, it did contain three site unit types (submesic, intermediate, and subxeric) within one treatment area. Guidelines in effect at the time the regeneration study was installed said that pine-hardwood regeneration should be restricted to south-facing slopes. This resulted in all plots in the regeneration study being located on subxeric ecological land classification units. At stand age 6, we installed four additional plots on the intermediate and submesic land units in one of the treatment areas of his study (two plots in each ecological unit), and compared the results with those on the subxeric units in the original study design. The results are presented in tables 1-3.

Table 1 shows that there is a dramatic change in hardwood stocking in terms of numbers of stems (greater than 6 feet tall) per acre between the submesic versus the intermediate and subxeric land units. Although pines (planted and naturally regenerated from seed) are present on all ecological units, table 2 shows pines making up only 15 percent of the total basal area on the submesic land units, compared to 45 and 46 percent, respectively, for intermediate and subxeric units. This is in spite of the fact that the numbers of pines are also much larger on the submesic site unit because of a large number of volunteers seeded in from an adjacent pine stand. Most of these volunteer pines will die from being overtopped by the vigorous hardwood regeneration. The planted pine component on the submesic unit appears to have sufficient height to become a viable part of the mature stand; however, these pines are smaller in diameter and height than the corresponding set of planted pines on the intermediate and subxeric land units.

Table 1—Hardwood stocking by ecological unit

Unit	Stems	Basal area
	No./acre	*Ft^2/acre*
Subxeric	760	6.8
Intermediate	920	5.6
Submesic	2960	16.8

Table 2—Planted pine stocking by ecological unit

Unit	Stems	Basal area	Survival
	No./acre	-------------Percent-------------	
Subxeric	140	46	72
Intermediate	130	45	76
Submesic	100	15	52

Table 3–Heights of dominant hardwoods and pines

Unit	Hardwoods	Pines
	-------------------*Feet* ------------------	
Subxeric	12.1	17.0
Intermediate	14.1	17.7
Submesic	16.4	15.4

Since the goal is to develop pine-hardwood mixtures, the 6-year, average cumulative height growth of dominant oaks and pines is presented in table 3. "Dominant" means the tallest hardwoods at a density (numbers per acre) equivalent to the pine planting density. The hardwoods display the expected growth patterns of increasing average height to increasing site quality represented by the ecological land units. The lower total height of pine on the submesic area (15.7 feet on the submesic compare to an average of 17.4 feet on the intermediate and subxeric units) is attributed to hardwood competition effects. A further indication of the hardwood competitive effect is that at age 6 on the submesic unit, the tallest hardwoods averaged a foot taller than the pines. Although it cannot be determined from this study, the results raise the question of whether the pines would have survived at all without the summer fire treatment that set back the initial hardwood growth response. These results offer a working hypothesis that this kind of ecological land classification system has potential for tailoring our forest operation prescriptions to the land. Further research is needed to fully test this hypothesis.

CONCLUSIONS

These studies suggest that forest operations designed to develop pine-hardwood mixtures can produce productive timber stands and diverse plant communities at a lower cost and with less degradation to site quality than the intensively site prepared, pine plantation system. Mixed pine-hardwood stands meet a wider array of land management objectives and require less costly (both environmentally and economically) forest operations. The resulting pine-hardwood forest operation systems are well suited to the economic conditions and land management needs of many NIPF landowners.

Ecological classification offers a tool for transferring research results to the particular management application, and a way to tailor forest operations within stands. Although results are preliminary, indications are that without the use of a post-harvest site preparation fire, pine-hardwood management in the Piedmont will not work better on ecological site units than intermediate, that is, the mesic and submesic land units of Jones' model. Although mesic and submesic ecological land units are scarce in the Piedmont relative to the area composed of intermediate and subxeric land units, they nevertheless are productive pine-hardwood sites suitable for sawtimber management, in which case post-harvest fire would likely be needed to get a pine component established.

LITERATURE CITED

Abercrombie, J.A., Jr.; Sims, D.H. 1986. Fell and burn for low-cost site preparation. Forest Farmer. 46(1):14-17.

Augspurger, M.K.; Van Lear, D.H.; Cox, S.K.; Phillips, D.R. 1987. Regeneration of hardwood coppice following clearcutting with and without prescribed fire. In: Phillips, Douglas R., comp. Proceedings of the fourth biennial southern silvicultural research Conference; 1986 November 4-6; Atlanta, GA. Gen. Tech. Rep. SE-42. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 89-92.

Ball, R.E.B.; Waldrop, T.A.; Jones, S.M. 1993. Distribution and development of root mats in the South Carolina Piedmont. In: Brissette, John C., ed. Proceedings of the seventh biennial southern silvicultural research conference; 1992 November 17-19; Mobile, AL. Gen. Tech. Rep. SO-93. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 229-234.

Geisinger, D.R.; Waldrop, T.A.; Haymond, J.L.; Van Lear, D.H. 1989. Sprout growth following winter and spring felling with and without summer broadcast burning. In: Waldrop, Thomas A., ed. Proceedings of pine-hardwood mixtures: a symposium on management and ecology of the type; 1989 April 18-19; Atlanta, GA. Gen. Tech. Rep. SE-58. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 91-95.

Evans, T. L.; Guynn, D.C., Jr.; Waldrop, T.A. 1991. Effects of fell-and-burn site preparation on the wildlife habitat and small mammals in the upper southeastern Piedmont. In: Nodvin, Steven C; Waldrop, Thomas A., eds. Fire and the environment: ecological and cultural perspectives: Proceedings of an international symposium. 1990 March 20-24; Knoxville, TN. Gen. Tech. Rep. SE-69. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 160-167.

Jones, S.M. 1989. Application of landscape ecosystem classification in identifying productive potential of pine-hardwood stands. In: Waldrop, Thomas A., ed. Proceedings of pine-hardwood mixtures: a symposium on management and ecology of the type; 1989 April 18-19; Atlanta, GA. Gen. Tech. Rep. SE-58. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 64-69.

Jones, S.M. 1991. Landscape ecosystem classification for South Carolina. In: Mengel, Dennis L.; Tew, D. Thompson, eds. Proceedings of a symposium: ecological land classification: applications to identify the productive potential of southern forests. 1991 January 7-9; Charlotte, NC. Gen. Tech. Rep. SE-68. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 59-68.

Lloyd, F.T.; White, D.L.; Abercrombie, J.A., Jr.; Waldrop, T.A. 1991. Releasing four-year-old pines in mixed shortleaf-hardwood stands. In: Coleman, Sandra S.; Neary, Daniel G., eds. Proceedings of the sixth biennial southern silvicultural research conference; 1990 October 30 - November 1; Memphis, TN. Gen. Tech. Rep. SE-70. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 852-857. 2 vol.

McGee, C.E. 1986. Regeneration after shear felling and chipping of upland hardwoods. Res. Pap. SO-224. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 13 p.

McGee, C.E. 1989. Converting low-quality hardwood stands to pine-hardwood mixtures. In: Waldrop, Thomas A., ed. Proceedings of pine-hardwood mixtures: a symposium on management and ecology of the type; 1989 April 18-19; Atlanta, GA. Gen. Tech. Rep. SE-58. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 107-111.

McMinn, J.W. 1989. Influence of whole-tree harvesting on stand composition and structure in the oak-pine type. In: Waldrop, Thomas A., ed. Proceedings of pine-hardwood mixtures: a symposium on management and ecology of the type; 1989 April 18-19; Atlanta, GA. Gen. Tech. Rep. SE-58. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 96-99.

Perry, C.J.; Waldrop, T.A. 1995. Opening size and site preparation techniques affect regeneration success for uneven-aged pine- hardwood mixtures. In: Edwards, M. Boyd, ed. Proceedings of the eighth biennial southern silvicultural research conference; 1994 November 1-3; Auburn, AL. Gen. Tech. Rep. SRS-1. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 406-142.

Phillips, D.R.; Abercrombie, J.A., Jr. 1987. Pine-hardwood mixtures-a new concept in regeneration. Southern Journal of Applied Forestry. 11(4):192-197.

Robichaud, P.R.; Waldrop, T.A. 1994. A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. Water Resources Bulletin. 30(1):27-34.

Stone, S.L.; Carraway, A.B.; Waldrop, T.A.; Robichaud, P.R. 1995. Impacts of burning severity on a southern Appalachian site. In: Edwards, M. Boyd, ed. Proceedings of the eighth biennial southern silvicultural research conference; 1994 November 1-3; Auburn, AL. Gen. Tech. Rep. SRS-1. Asheville, NC: U.S. Department of

Agriculture, Forest Service, Southeastern Forest Experiment Station: 613-619.

Van Lear, D.H.; Kapeluck, P.R. 1989. Fell and burn to regenerate mixed pine-hardwood stands: an overview of effects on soil. In: Waldrop, Thomas A., ed. Proceedings of pine-hardwood mixtures: a symposium on management and ecology of the type; 1989 April 18-19; Atlanta, GA. Gen. Tech. Rep. SE-58. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 83-90.

Van Lear, D.H.; Danielovich, S.J. 1988. Soil movement after broadcast burning in the Southern Appalachians. Southern Journal of Applied Forestry. 12:49-53.

Waldrop, T.A. 1991. Pine-hardwood regeneration in small openings for uneven-aged management. In: Coleman, Sandra S.; Neary, Daniel G., eds. Proceedings of the sixth biennial southern silvicultural research conference; 1990 October 30 - November 1; Memphis, TN. Gen. Tech. Rep. SE-70. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 398-408. 2 vol.

Waldrop, T.A. 1995. Variations in the fell-and-burn system to regenerate pine-hardwood mixtures in the Piedmont. In: Edwards, M. Boyd, ed. Proceedings of the eighth biennial southern silvicultural research conference; 1994 November 1-3; Auburn, AL. Gen. Tech. Rep. SRS-1. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 401-405.

Waldrop, T.A. [In press]. Four site-preparation techniques for regenerating pine-hardwood mixtures in the Piedmont. Southern Journal of Applied Forestry.

Waldrop, T.A.; Lloyd, F.T.; Abercrombie, J.A., Jr. 1989. Fell and burn to regenerate mixed pine-hardwood stands: an overview of research on stand development. In: Waldrop, Thomas A., ed. Proceedings of pine-hardwood mixtures: a symposium on management and ecology of the type; 1989 April 18-19; Atlanta, GA. Gen. Tech. Rep. SE-58. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 75-83.

Williams, D.L.; Waldrop, T.A. 1995. Felling and burning to prepare southern Appalachian sites occupied by mountain laurel. In: Edwards, M. Boyd, ed. Proceedings of the eighth biennial southern silvicultural research conference; 1994 November 1-3; Auburn, AL. Gen. Tech. Rep. SRS-1. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 623-625.

CHARACTERIZATION OF DISTURBED FOREST SOILS IN THE LOWER COASTAL PLAIN OF SOUTH CAROLINA

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Abstract—Wet site harvesting operations may cause severe soil disturbances that may reduce long-term site productivity. Voluntary Forestry Best Management Practices (BMPs) have been developed to minimize and ameliorate the disturbances. However, the effects of soil disturbance on long-term productivity and the effects of amelioration techniques on site hydrology are uncertain. The objectives of this study were to characterize disturbed forest soils to understand the mechanisms of the disturbance and the potential effects on site hydrology and site productivity. The study site is located in an intensively managed loblolly pine plantation in the lower coastal plain of South Carolina. Dry and wet weather harvesting treatments were installed in summer 1993 and winter 1994, respectively. Soil profiles were described for recently disturbed, deeply rutted areas and 2-year-old, deeply rutted and churned areas. Intact soil core samples were collected from each morphological section for soil physical and hydraulic characterizations. Soil profile descriptions disclosed significant soil structural changes and increased redoximorphic features caused by deep ruts indicating decreases in hydraulic conductivity. Preliminary results of soil physical and hydraulic properties indicated significant change in the site hydrology. Although recent deep ruts showed directional hydraulic characteristics, the characteristics disappeared 2 years after the disturbances, which suggested that natural soil restructuring processes were taking place.

INTRODUCTION

Long-term forest productivity of intensively managed pine plantations has become a major concern among natural resource managers and environmental conservationists since the 1950's, when harvesting operations became more mechanized. Heavy harvesting equipment may cause severe soil disturbance when forest sites are wet. A number of studies around the world have indicated that forest productivity may decline under certain circumstances (Powers and others 1990). In a review paper by Powers and others (1990), decreased productivity of Norway spruce [*Picea abies* (L.) Karst] in Europe, radiata pine (*Pinus radiata* D. Don) plantations in Australia, and Scots pine (*P. sylvestris* L.) in eastern Germany were caused by organic matter decreases and/or soil compaction which created poor drainage. These soil changes caused nutrient deficiencies and created an imbalance in soil water and air availability.

In the U.S. southeastern coastal plain, pine flatwood productivity declines were also reported. Gholz and Fisher (1983) estimated that a natural long leaf pine (*P. palustris* Mill.) forest produced approximately 450 to 600 cubic meters per hectare, almost twofold the productivity of current slash pine (*P. elliottii* Engelm.) plantations, and concluded that organic matter removal during intensive harvesting and site preparation operations caused productivity decreases on the typical flatwood soils (Typic and Ultic Haplaquods) found in their study sites. Tiarks and Haywood (1996) evaluated the effect of disking and bedding site preparations on the productivity of slash pine plantations in the West Gulf Coastal Plain of Louisiana. They concluded that site preparation in the first rotation depleted nutrients and decreased second-rotation pine height.

Earlier researchers recognized severe disturbance after harvesting and its negative effects on tree growth. Pearson and Marsh (1935) found that soil disturbance by grazing and logging operations on wet clayey-textured soil created adverse conditions for seedling establishment because of reduced water and air permeability. Moehring and Rawls (1970) documented organic matter loss from sites harvested under dry conditions, and organic matter loss and soil compaction, puddling, and smearing on sites harvested under wet conditions. Youngberg (1959) reported that a significant increase in bulk density in the surface 0 to 30 centimeters, and a decrease in organic matter on tractor roads reduced soil aeration and created a nitrogen deficiency. These effects significantly decreased Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] seedling growth. Hatchell and others (1970) found that a significant change after harvesting in soil physical properties in low-lying wet areas reduced loblolly pine (*P. taeda* L.) seedling growth. Scheerer and others (1994) compared loblolly pine seedling response between rutted and undisturbed sites and found higher mortality and lower seedling growth in the rutted sites. They concluded that the results were caused by a higher water table, decreased saturated hydraulic conductivity, and decreased soil drainage due to the soil disturbance.

Although numerous studies have characterized compacted agricultural and forestland soils (Hillel 1982, Pritchett and Fisher 1987, Marshall and others 1996), the morphology and physical characteristics of deeply rutted and churned forest soils are not well documented. Burger and others (1988) found that soil horizons may be severely disturbed in wet skid trails. Aust and others (1995) compared dry and wet weather harvesting effects on soil physical properties in a wet pine flat. They concluded that dry weather harvesting created soil compaction and subsequent soil physical property changes on primary and secondary skidding trails,

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and wet weather harvesting created more severe soil disturbance and complex soil physical property changes which increased water tables.

Severe disturbance can cause drastic soil hydraulic property alteration. Rutted and churned soils have different soil water release patterns than undisturbed soils (Jamison 1963, Gradwell 1966, Huang and others 1996). Jamison (1963) conducted a laboratory experiment of disturbed soil physical properties and found that macroporosity and available water-holding capacity of puddled soils were significantly lower than those of other disturbed soils. Huang and others (1996) reported significant decreases of sorptivity and unsaturated hydraulic conductivity after harvesting operations. These laboratory experiments and field studies indicate that puddled soils contain less available water and lower water infiltration rates, both of which create less desirable conditions for seedling growth. Forest soil disturbances produced by heavy equipment are deeper and more severe than pasture soil disturbances, suggesting that heavier equipment may have a more significant effect on soil physical and hydrological properties and future forest productivity.

Despite the concern among environmental managers and the efforts of many researchers, the soil disturbance effect on site hydrology and future forest productivity is still relatively unknown, and harvesting and amelioration techniques on wet sites have not been rigorously evaluated. Therefore, detailed characterization of disturbed forest soils is critical for understanding mechanisms of disturbance and for predicting potential effects on site hydrology and site productivity. The objectives of this study are to characterize disturbed forest soil morphology and physical properties in order to understand the processes that control site hydrology and productivity.

MATERIALS AND METHODS

This disturbed soil characterization study was conducted as part of a long term soil productivity study located in an intensively managed loblolly pine plantation in the lower coastal plain of South Carolina. The area is a typical wet pine flat. The majority of the soils within the study area were Typic Ochraqualfs. These Alfisols typically have a heavy clay argillic Bt horizon at a depth of 50 to 60 centimeters and an incipient E horizon just above the Bt. Drainage classes of these soils are intermediate to poorly drained, as indicated by “aquic” suborder or subgroup taxonomic classes, and these soils are considered hydric soils (Soil Conservation Service 1991).

The study was established in 1991 and included dry and wet weather harvesting and several mechanical treatments. Details of the study layout and project design are contained in Preston (1996). Dry and wet weather harvesting treatments were installed in summer 1993 and winter 1994, respectively, and site preparation treatments were installed in fall 1995.

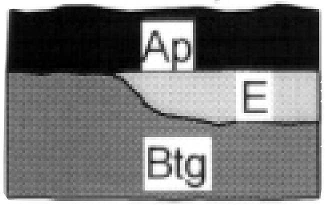
Soil profiles were described at 2-year-old deeply rutted and churned areas within the wet, nonbedded plots of the study site and at recently created deep ruts on similar soils near the study site. Intact soil core samples were collected from each morphological section (horizons) (Blake and Hartge 1986) in horizontal and vertical directions. These intact cores were used for soil physical characterization and directional hydraulic characterization. Soil physical characterization included bulk density (Blake and Hartge 1986) and macro-, micro-, and total porosity (Danielson and Sutherland 1986). Hydraulic characterization included saturated hydraulic conductivity (Klute and Dirksen 1986) and air permeability (Groenevelt and Lemoine 1987). Soil structural stability index, expressed as the ratio between air permeability and water permeability (k_{air}/k_{water}) (Whelan and others 1995), was also measured to evaluate soil structural changes resulting from soil disturbances. Water permeability (k_{water}) was calculated from saturated hydraulic conductivity by an equation developed by Hubbert (1940). Soil strength of each morphological section was measured using a pocket penetrometer (Bradford 1986). These results were compared to typical intact and undisturbed soil profile descriptions (Soil Conservation Service 1982) and soil physical properties reported by Burger (1994).

RESULTS AND DISCUSSION

Soil Profile Description

The soil profile descriptions revealed that significant changes had occurred in surface and subsurface horizons (fig. 1). Typical undisturbed soils contained incipient E horizons and well-developed argillic horizons (Soil Conservation Service 1982). All disturbed soils contained disturbed surface and subsurface horizons above undisturbed subsurface horizon (Bt or Btg), and no E horizon was observed in any disturbed soils (fig. 1). Disturbed surface horizon was designated as Ap or Ap1, and surface horizon within the ruts was designated as Ap’. Disturbed subsurface horizons were designated as Ap2 and Ap3 in the fresh, deep ruts, Ap2 and Apg in the 2-year-old deep ruts, and Apg in the 2-year-old churn. Disturbed subsurface horizons were characterized by loam to silty clay textures, which were probably caused by physical mixing of surface and subsurface soils. Gray or dark grayish matrix colors were common, due to the inclusion of few-to-many distinctive mottles. Structure was predominantly massive with fragments of weak platy or subangular blocky structure caused by normal and shear stresses from surface disturbances. These characteristics indicated a change in saturated hydraulic conductivity or internal soil water drainage patterns. Burger and others (1988) reported similar soil characteristics caused by the wet weather harvesting operations and found severely disturbed subsurface soil horizons under the disturbed surface horizon.

Distinctive characteristics of the deeply rutted soils are deep skidding ruts and associated disturbed soil structures within the ruts (fig. 1). Fresh deep ruts contained a churned and compressed horizon (Ap’) along the side and bottom of ruts. Many coarse, prominent, mottle patterns, oriented with a weak medium platy structure in the horizon, indicated restricted water movement (low lateral water flow from ruts

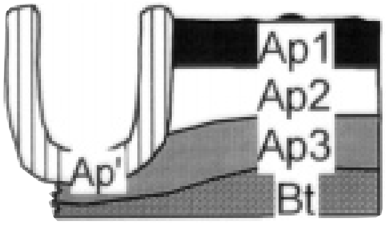


Undisturbed (Soil Conservation Service 1982)

Ap ---- 0 to 13 centimeters; very dark gray (10YR3/1) loam; moderate medium granular structure; friable; many fine, common medium, and common large roots; very strongly acid; clear wavy boundary.

Btg1 ---- 13 to 86 centimeters; grayish brown (10YR5/2) clay; common medium distinct brownish yellow (10YR6/6) mottles; moderate medium subangular blocky structure; firm; sticky; plastic; few fine and few medium roots; prominent clay film on faces of peds; few fine flakes of mica; very strongly acid; gradual smooth boundary.

Btg2 ---- 86 to 145 centimeters; gray (10YR5/1) clay; common medium distinct olive brown (2.5Y4/4) mottles; moderate medium subangular blocky structure; firm; very sticky; very plastic; few fine roots; thin patchy clay film on face of peds; few fine flakes of mica; medium acid.



Fresh deep ruts

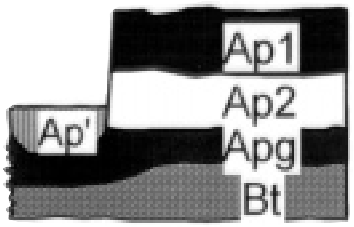
Ap1 ---- 0 to 25 centimeters; very dark gray (10YR3/1) silt loam; weak fine granular structure; firm; nonsticky; nonplastic; few fine roots; abrupt wavy boundary.

Ap2 ---- 25 to 51 centimeters; dark grayish brown (2.5Y4/2) loam; few fine prominent yellowish brown (10YR5/6) and gray (10YR5/1) mottles; massive structure with fragments of weak medium subangular blocky and platy; firm; slightly sticky; slightly plastic; few fine roots; clear wavy boundary.

Ap3 ---- 51 to 76 centimeters; light yellowish brown (2.5Y6/4) silty clay loam; common medium distinct reddish yellow (7.5YR6/8) and grayish brown (2.5Y5/2) mottles; massive structure with weak medium subangular blocky; friable; slightly sticky; slightly plastic; few fine roots; clear wavy boundary.

Bt ---- 76 to 102 centimeters; light olive brown (2.5Y5/4) silty clay; common medium distinct yellowish red (5YR5/8) and weak red (2.5YR5/2) mottles; moderate fine subangular blocky structure; friable; slightly sticky; slightly plastic; few medium roots; few faint clay film on faces of peds.

Ap' ---- olive (5Y5/3) loam; many coarse prominent yellowish brown (10YR5/8) and grayish brown (2.5Y5/2) mottles; weak medium platy structure; slightly plastic; few very fine roots; clear irregular boundary.



2-yr old deep ruts

Ap1 ---- 0 to 8 centimeters; very dark grayish brown (10YR3/2) silt loam; weak fine granular structure; friable; nonsticky; nonplastic; common very fine roots; clear smooth boundary.

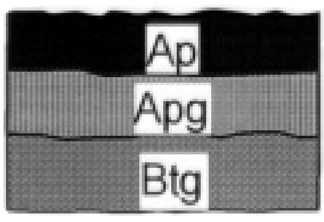
Ap2 ---- 8 to 33 centimeters; dark grayish brown (2.5Y4/2) fine sandy clay loam; few fine prominent strong brown (7.5YR5/8) and gray (N5/0) mottles; massive structure; slightly sticky; slightly plastic; few very fine roots; gradual wavy boundary.

Apg ---- 33 to 61 centimeters; olive (5Y5/3) silty clay; many coarse prominent (5GY5/1) and yellowish brown (10YR5/8) mottles; massive structure with fragments of weak medium platy; slightly sticky; slightly plastic; few very fine roots; common faint stress surfaces on face of peds; gradual wavy boundary.

Bt ---- 61 to 102 centimeters; olive (5Y5/3) fine sandy clay; many medium prominent yellowish brown (10YR5/6) and gray (N5/0) mottles; moderate coarse subangular blocky structure; firm; sticky; slightly plastic; few fine roots; few faint clay film on faces of peds.

Ap' ---- very dark grayish brown (2.5Y3/2) loam; weak fine granular structure; nonsticky; nonplastic; common very fine roots; clear irregular boundary.

2-yr old churn



Ap ---- 0 to 28 centimeters; very dark gray (5YR3/1) silt loam; moderate medium granular/massive structure; firm; nonsticky; nonplastic; many very fine roots; abrupt wavy boundary.

Apg ---- 28 to 48 centimeters; very dark gray brown (10YR3/1) silty clay loam; many medium prominent dark reddish brown (5YR3/4) and very dark gray (10Y3/1) mottles; massive structure; firm; slightly sticky; plastic; common very few fine roots; clear wavy boundary.

Btg ---- 48 to 89 centimeters; olive (5Y5/3) silty clay; many fine prominent dark gray (N4/0) and brownish yellow (10YR6/8) mottles; moderate medium subangular blocky structure; firm; sticky; slightly plastic; few fine roots; few faint clay film on face of peds; few medium irregular carbonates concretion.

Figure 1—Soil profile descriptions of undisturbed and disturbed soils in the lower coastal plain wet pine flats.

into soil). This reduced water flow probably caused higher water tables and slower drainage in the rutted sites. Two years after the disturbance, this churned horizon was weathered and deposited in the bottom of ruts (Ap') (fig. 1). This deposited horizon had relatively high organic matter and weak fine granular structure. Consequently, a cross section of soil horizons was exposed in the side of the ruts, and lateral water infiltration was less restricted, which may have improved site hydrology.

Soil Physical and Hydraulic Properties

Although harvesting operations caused extensive rutting, the soil physical properties were not altered in the surface horizons to the same extent as in the subsurface horizons. Disturbed surface horizons (Ap and Ap1) generally had lower bulk density and higher porosity, strength, and saturated hydraulic conductivity than disturbed subsurface soils, and those properties were relatively similar to the undisturbed surface soil properties (table 1). Negative soil physical property changes in surface horizons, which had been reported by many studies (Pearson and March 1935, Youngberg 1959, Moehring and Rawls 1970, Hatchell and others 1970, Aust and others 1993, 1995), were probably prevented by mixing various sizes of organic debris during the operation. In 2-year-old, deep ruts, natural weathering processes formed the Ap' in the bottom of the ruts (fig. 1); therefore, the Ap' properties were very close to the undisturbed surface horizon.

Although the disturbed subsurface horizons have intermediate soil textures between Ap and Bt horizons (fig. 1), the physical and hydraulic properties of the disturbed horizons were more similar to the Bt horizon (table 1). Bulk density of the disturbed subsurface horizons ranged between 1.29 to 1.47 megagrams per cubic meter, similar to the bulk density of the Bt horizons which ranged between 1.25 to 1.48 megagrams per cubic meter. These high bulk density may restrict root penetration since a bulk density of 1.4 megagrams per cubic meter commonly limits root growth.

Porosity of the disturbed subsurface horizons was similar to those of Bt horizons. Macro-, micro-, and total porosity of

Table 1—Soil physical and hydraulic properties of undisturbed and disturbed soils in a wet pine flat[a]

Horizon	BD[b]	n_{macro}[c]	n_{micro}	n_{total}	σ[d]	K_{sat}[e]	k_{air}[f]	k_{air}/k_{water}[g]
	Mg/m³	----------------*Percent*----------------				*Kg/cm²*	*m/day*	*m²x10⁻¹³*
Undisturbed[h]								
Ap	1.18	13.1	39.1	52.2	NA	8.22	NA	NA
E	1.64	14.5	21.2	35.7	NA	0.72	NA	NA
Bt	1.45	6.1	40.5	47.0	NA	0.09	NA	NA
Fresh deep ruts								
Ap1	1.05 a[i]	4.0 a	38.9 a	42.9 a	1.61 a	3.12	1.72 ab	15.6 a
Ap2	1.46 c	1.3 b	31.0 b	32.3 b	1.81 a	0.02	2.19 a	22.7 a
Ap3	1.47 c	0.9 b	31.4 b	32.5 b	2.29 b	0.00	1.46 ab	93.4 b
Bt	1.25 b	2.5 ab	36.2 a	38.7 a	1.56 a	0.05	1.88 ab	63.6 ab
Ap'	1.45 c	0.9 b	31.8 b	32.7 b	1.76 a	0.01	0.96 b	27.4 a
2-yr-old deep ruts								
Ap1	1.11 a	5.7 a	43.5 a	49.2 a	0.43 b	2.73	2.48 ab	0.77 a
Ap2	1.47 c	1.6 b	30.3 c	31.9 c	0.99 c	0.00	2.17 ab	94.6 b
Apg	1.29 b	1.3 b	37.6 b	38.9 b	0.82 c	0.00	1.65 bc	86.3 b
Bt	1.48 c	1.1 b	28.1 c	29.2 c	1.53 d	0.00	0.83 c	52.8 ab
Ap'	1.09 a	5.1 a	38.4 b	43.5 b	0.14 a	3.57	2.84 a	0.97 a
2-yr-old churn								
Ap	0.62 a	8.5 a	48.7 a	57.2 a	0.26 a	14.2 a	2.65 a	0.06 a
Apg	1.35 b	3.4 b	31.1 b	34.5 b	0.95 b	0.03 b	2.85 a	102.5 b
Btg	1.43 c	1.6 b	30.5 b	32.1 b	1.48 c	0.02 b	1.47 b	21.2 ab

[a] Values are means of six samples.
[b] Bulk density.
[c] Macro, micro, and total porosity.
[d] Soil strength, corresponding gravimetric soil moisture content are Ap ≅ 15% and B and C ≅ 18-26%.
[e] Saturated hydraulic conductivity.
[f] Air permeability.
[g] Soil structure index.
[h] Data are from Burger 1994, and no statistical analysis is available.
[i] Means followed by the same letter within a column and soil profile are not significantly different according to Fisher's LSD at a 0.05 probability level.

disturbed subsurface horizons ranged 0.9 to 3.6 percent, 30.3 to 37.6 percent, and 31.9 to 38.9 percent, respectively (table 1). These results were clearly lower than those of surface horizons but similar to those of undisturbed subsurface horizons. The lower macro- and micro-porosity and higher bulk density values of the disturbed horizons suggested that their water holding capacities were decreased significantly.

Saturated hydraulic conductivity was so variable that statistical differences were not discernible among horizons. However, the data trends indicated that the disturbed subsurface horizons had significantly lower saturated hydraulic conductivity than the surface horizons, but they were not significantly different from Bt horizons (table 1). The low saturated hydraulic conductivity of disturbed horizons was caused by the lower macro-porosity and reduced total porosity. Aust and others (1993, 1995) found similar results in lower coastal plain wet pine flats.

Disturbance altered the intrinsic permeability of subsurface horizons. The air permeability of disturbed subsurface horizons was relatively higher than that of associated Bt horizons, and their stability indexes were significantly higher than those of other horizons because of the high ratio between air and water permeability (table 1). Hubbert (1940) showed that permeability was a function of matrix structure, not a function of media. Therefore, as structure becomes more stable, the stability index approaches 1 (Whelan and others 1995). The high stability index of the disturbed horizons indicated weakened soil structure and decrease of internal drainage due to the disturbance, which explained the massive soil structure and gray mottling in the soil profile descriptions (fig. 1).

Soil strength is an integrated measurement of soil properties. Soil strengths of disturbed horizons in the 2-year-old, deep ruts and churn were significantly lower than these of associated Bt horizons, even though the bulk density values of the disturbed horizons were about the same as those of the Bt horizons (table 1). This is explained by physical mixing of the soils, alteration of soil textures, massive soil structures (fig. 1), and higher soil stability indexes of the disturbed horizons.

Directional Hydraulic Properties

Fresh deep ruts had significantly different vertical and horizontal air permeability values among horizons (table 2). Vertical air permeability was higher than horizontal air permeability in the surface horizon (Ap1), which indicated that infiltration of surface water was not restricted. However, in the disturbed subsurface horizons (Ap2 and Ap3), vertical air permeability was lower than horizontal air permeability, which indicated a restriction of vertical permeability. These characteristics probably caused a higher water table in the disturbed sites. In the churned horizon inside of the ruts (Ap'), vertical air permeability (parallel to the platy structure) was higher than horizontal air permeability (perpendicular to the platy structure), which indicated low water infiltration from ruts into the soil. This was probably causing slower drainage in the disturbed site. However, 2-year-old, deep ruts and churned soils did not show directional permeability differences, which indicates that natural soil restructuring processes occurred during the 2 years.

Table 2—Vertical and horizontal direction air permeability measurements in the fresh deep ruts[a]

Direction	Ap1	Ap2	Ap3	Bt	Ap'
Vertical	2.17[b]	1.97	1.36	2.64	1.55
Horizontal	1.25	2.42	1.57	1.12	0.36

[a] Values are means of three samples.
[b] Overall p-value = 0.022 from ANOVA test.

CONCLUSIONS

Preliminary results of soil profile descriptions and soil physical and hydraulic property measurements described disturbed soil characteristics. Although harvesting operations caused extensive rutting, the soil physical properties of the surface horizons were not altered because of incorporation of organic matter. However, disturbed subsurface horizons were affected significantly by the operations. Soil profile descriptions showed that the disturbed subsurface horizons had different horizonations, mixed texture, weakened structure, and increased redoximorphic features. Significant soil physical and hydraulic property changes indicated lower water-holding capacity and available water for plant growth, and slower internal drainage and water sorptivity, which explained the higher water table, slower site drainage pattern, and consequent alteration of site hydrology. The difference between vertical and horizontal air permeability in the fresh deep ruts indicated restricted surface water infiltration and limited lateral perched water flow through the ruts. However, this restricted water movement was improved after 2 years, probably due to natural soil restructuring processes.

This study showed that altered properties of the disturbed subsurface horizons remained 2 years after disturbance. Bedding is a common site preparation technique used in wet pine flats to ameliorate the soil disturbances. Although Gent and others (1983) found that bedding site preparation did not ameliorate disturbed subsurface horizons, a number of other studies showed that bedding improved surface soil conditions and seedling survival in wet sites (Haines and Prichett 1964, Derr and Mann 1977, Pritchett 1979, Sarigumba and Anderson 1979, Shiver and Fortson 1979). Therefore, bedding site preparation is probably the best current solution for disturbed soil amelioration, although long-term effect of disturbed subsurface horizons on site hydrology and future productivity is still unknown.

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LITERATURE CITED

Aust, W.M.; Reisinger, T.W.; Burger, J.A.; Stokes, B.J. 1993. Soil physical and hydrological changes associated with logging a wet pine flat with wide-tired skidders. Southern Journal of Applied Forestry. 17:22-25.

Aust, W.M.; Tippett, M.D.; Burger, J.A.; McKee, W.H., Jr. 1995. Compaction and rutting during harvesting affect better drained soils more than poorly drained soils on wet pine flats. Southern Journal of Applied Forestry. 19:72-77.

Blake, G.R.; Hartge, K.H. 1986. Bulk density. In: Klute A., ed. Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Madison, WI: ASA and SSSA: 363-375.

Bradford, J.M. 1986. Penetrability. In: Klute A., ed. Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Madison, WI: ASA and SSSA: 463-478.

Burger, J.A.; Wimme, K.J.; Stuart, W.B.; Walbridge, T.A., Jr. 1988. Site disturbance and machine performance from tree-length skidding with a rubber-tired skidder. In: Proceedings, 5th Biennial Southern Silviculture Research Conference. Gen. Tech. Rep. SO-74. U.S. Department of Agriculture, Forest Service. 618 p.

Burger, M.A. 1994. A wetland trafficability hazard index based on soil physical properties and site hydrology evaluations. Blacksburg, VA: Virginia Polytechnic Institute and State University, Blacksburg. 138 p. thesis.

Danielson, R.E.; Sutherland, P.L. 1986. Porosity. In: Klute, A., ed. Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Madison, WI: ASA and SSSA: 443-461.

Derr, H.J.; Mann, W.F., Jr. 1977. Bedding poorly drained sites for planting loblolly and slash pines in southwest Louisiana. Res. Pap. SO-134, New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experimentt Station. 5 p.

Gent, J.A. Jr.; Ballard, R.; Hassan, A.E. 1983. The impact of harvesting and site preparation on the physical properties of lower coastal plain forest soils. Soil Science Society American Journal. 47:595-598.

Gholz, H.L.; Fisher, R.F. 1983. The limits of productivity: Fertilization and nutrient cycling in coastal plain slash pine forests. In: Stone E.L., ed. Forest soils and treatment impacts. Proceedings 6th North American Forest Soils Conference; Knoxville, TN: University of Tennessee: 105-120.

Gradwell, M.W. 1966. Soil moisture deficiencies in puddled pastures. New Zealand Journal of Agricultural Research. 9:127-136.

Groenevelt, P.H.; Lemoine, G.G. 1987. On the measurement of air permeability. Netherlands Journal of Agricultural Science. 35:385- 394.

Haines, L.W.; Pritchett, W.L. 1964. The effect of site preparation on the growth of slash pine. Proceedings Soil and Crop Science Society of Florida. 24:27-34.

Hatchell, G.E.; Ralston, C.W.; Foil, R.R. 1970. Soil disturbances in logging. Journal of Forestry. 68:772-775.

Hillel, D. 1982. Introduction to soil physics. San Diego: Academic Press.

Huang, J.; Lacey, S.T.; Ryan, P.J. 1996. Impact of forest harvesting on the hydraulic properties of surface soil. Soil Science. 161:79- 86.

Hubbert, M.K. 1940. The theory of groundwater motion. Journal of Geology. 48:785-944.

Jamison, V.C. 1963. Changes in air-water relationships due to structural improvement of soils. Soil Science. 76:143-151.

Klute, A.; Dirksen C. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In: Klute A., ed. Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Madison, WI: ASA and SSSA: 687-734.

Marshall, T.J.; Holmes, J.W.; Rose, C.W. 1996. Soil Physics. Cambridge: Cambridge University Press.

Moehring, D.M.; Rawls, I.W. 1970. Detrimental effects of wet weather logging. Journal of Forestry. 68:166-167.

Pearson, G.A.; Marsh, R.E. 1935. Timber growing and logging practice in the Southwest and in the Black Hills region. Tech. Bull. 480. Washington, DC: U.S. Department of Agriculture. 80 p.

Powers, R.F.; Alban, D.H.; Miller, R.E.; [and others]. 1990. Sustaining site productivity in North American forests: Problems and prospects. In: Gessel, S.P.; Lacata, D.S.; Weetman, G.F.; Powers, R.F., eds. Sustained productivity of forest soils. Proceedings, 7th North American Forest Soils Conference, Vancouver, B.C.: University of British Columbia, Faculty of Forestry Publishers: 49-79.

Preston, D.P. 1996. Harvesting effects on the hydrology of wet pine flats. Blacksburg, VA: Virginia Polytechnic Institute and State University, Blacksburg. 126 p. thesis.

Pritchett, W.L. 1979. Site preparation and fertilization of slash pine on a wet savanna soil. Southern Journal of Applied Forestry. 3:86-90.

Pritchett, W.L.; Fisher, R.F. 1987. Properties and management of forest soils. New York: John Wiley & Sons. 494 p.

Sarigumba, T.I.; Anderson, G.A. 1979. Response of slash pine to different spacings and site-preparation treatments. Southern Journal of Applied Forestry. 3:91-94.

Scheerer, G.A.; Aust, W.M.; Burger, J.A.; McKee, W.H., Jr. 1994. Skid trail amelioration following timber harvests on wet pine flats in South Carolina: 2-year results. In: Proceedings, 8th Biennial Southern Silviculture Research Conference. Gen. Tech. Rep. SRS-1. U.S. Department of Agriculture, Forest Service: 236-243.

Shiver, B.D.; Fortson, J.C. 1979. Effect of soil type and site-preparation method on growth and yield of flatwoods slash pine plantations. Southern Journal of Applied Forestry. 3:95-100.

Soil Conservation Service. 1982. Soil survey of Colleton County South Carolina. U.S. Department of Agriculture, Soil Conservation Service, in cooperation with South Carolina Agricultural Experiment Station and South Carolina Land Resources Conservation Commission.

Soil Conservation Service. 1991. Hydric soils of the United States. 3rd ed. Misc. Pub. No.1491. U.S. Department of Agriculture Soil Conservation Service in cooperation with the National Technical Committee for Hydric Soils, Washington, DC.

Tiarks, A.E.; Haywood, J.D. 1996. Site preparation and fertilization effects on growth of slash pine for two rotations. Soil Science Society American Journal. 60:1654-1663.

Whelan, B.M.; Koppi, A.J.; McBratney, A.B.; Dougherty, W.J. 1995. An instrument for the in situ characterization of soil structural stability based on the relative intrinsic permeabilities to air and water. Geoderma. 65:209-222.

Youngberg, C.T. 1959. The influence of soil conditions, following tractor logging, on the growth of planted Douglas-fir seedlings. Soil Science Society American Proceedings. 23:76-78.

AMELIORATION OF COMPACTED AND RUTTED SKID TRAILS ON WET PINE FLATS: FOURTH-YEAR RESULTS

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Abstract—Wet-weather harvesting operations on wet pine flats can cause soil disturbance that may reduce long-term site productivity. Site preparation and fertilization are often recommended as ameliorative practices for such disturbances, but few studies have actually quantified their effects on restoration. The purposes of this study were to quantify the effects of wet-weather harvest traffic on soil properties and loblolly pine (*Pinus taeda*) growth, and to evaluate the ameliorative effects of site preparation. Study sites were established on wet pine flats of the lower coastal plain within the Francis Marion National Forest (Berkeley County, SC). Eight replications were installed on sites that were salvage logged during wet soil conditions, following Hurricane Hugo. Treatments were arranged in a split-split plot within a completely randomized block design. Treatments were two levels of traffic (nontrafficked, trafficked), four levels of mechanical site preparation (none, disking, bedding, disking with bedding), and two levels of fertilization (none, 300 pounds per acre of 10-10-10 fertilizer). Initially, the trafficking increased soil bulk densities and reduced soil water movement and subsequent growth of loblolly pine. Bedding combined with fertilization restored site productivity to nontrafficked levels within 4 years, but disking or fertilization treatments alone were not effective at ameliorating the traffic effects. The effectiveness of the bedding and fertilization treatments for amelioration of traffic effects was probably related to the relatively small area of disturbed skid trails (<10 percent) found on these sites. Areas having more severe disturbance or higher percentages of disturbance might not be ameliorated as rapidly.

INTRODUCTION

Wet pine flats of the southeastern coastal plain typically have coarser textured surface soil horizons over finer textured argillic horizons (Allen and Campbell 1988). Consequently, vertical soil water movement is often limited by the subsurface horizon, while the almost level topography of the lower coastal plain limits horizontal water movement within the surface horizon. Thus, these wet pine flats often have perched water tables in close proximity to the soil surface. However, wet pine flats are often specifically selected for wet weather harvesting operations because of the slow water movement within the subsurface soils. Following rainfall events, the surface soil horizons moisten within hours, but the argillic horizons moisten very slowly. Therefore, the subsurface soil horizon retains high soil strength, even after rainfall events, which can support heavy harvesting equipment until the horizon eventually moistens. Loggers often refer to such sites as having a “hard bottom” and operations can continue on these sites long after rainfall events have halted operations in other areas. However, these wet weather harvesting operations can result in considerable amounts of soil compaction and rutting, which have been suggested as possible causes of reduced long-term site productivity (Aust and others 1993, Burger and others 1989, Childs and others 1989, Hatchell and others 1970, Lockaby and Vidrine 1984).

Soil aeration and soil nutrition are often limiting factors on wet pine flats (McKee and Hatchell 1987). Harvest operations that rut and compact soils have been shown to reduce soil water movement and soil oxygen levels, and reduce the volume of soil from which nutrients can be extracted (Aust and others 1995). The natural recovery time of wet pine flats from harvest disturbances has been estimated as being 15-20 years (Hatchell and Ralston 1971). Therefore, several researchers have proposed that these mechanical and chemical amendments should be used for amelioration of disturbed forest soils (Foil and Ralston 1967, Gent and others 1983, Hatchell 1981, McKee and Hatchell 1987, Tiarks and Haywood 1996, Wilhite and McKee 1986). The normal technique for the establishment of loblolly pine (*Pinus taeda*) plantations on wet flats usually entails some combination of mechanical site preparation or fertilization (Allen and Campbell 1988). The objectives of our investigation were to determine whether wet weather harvest traffic affected soil, hydrologic, and site productivity parameters and whether such disturbances could be ameliorated by site preparation and fertilization.

METHODS

Study Site

The research was conducted on wet pine flats located within the Francis Marion National Forest in Berkeley County, SC. These lower coastal plain sites were somewhat poorly to poorly drained. The Francis Marion National Forest was heavily damaged by Hurricane Hugo in September 1989, and many salvage operations were conducted during saturated soil conditions in an effort to salvage downed wood and reduce subsequent wildfire fuel loads. In effect, many of these salvage operations were clearcuts because fewer than five live trees per acre remained following the storm. Sites were selected so that within-site soil variation was limited to one soil series. Three soil series were identified across all sites. The very poorly drained to poorly drained Bethera series is a clayey, mixed, thermic, typic Paleaquult. A typical Bethera series profile consisted of a

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loamy surface underlain by a clay-textured argillic horizon. The poorly drained Rains series is a fine-loamy, siliceous, thermic Typic Paleaquults. The Rains series had a sandy loam surface texture and sandy clay loam subsurface texture. Both the Bethera and Rains series are hydric soils. The nonhydric, somewhat poorly drained Lynchburg series was identified on only one site. The Lynchburg series is a fine-loamy siliceous, thermic Aerenic Paleaquult having sandy loam surface textures underlain by sandy clay loams (USDA Soil Conservation Service 1980).

Treatments

All sites were salvage-logged with chainsaw felling and grapple skidders during saturated soil conditions in the late fall and winter of 1989. In winter 1989 and spring 1990, 12 sites were selected. Each site represented one replication. All sites were typical wet-weather harvests, each had obviously compacted and rutted primary skid trails (< 10 percent of the total area) and nontrafficked areas. Eight 20-feet by 80-feet treatment plots were located within each site. Four of these treatment plots were located in the trafficked primary skid trails and four were located in the nontrafficked areas. During 1990, soil physical, soil chemical, and site hydrological evaluations were completed as reported by Tippett (1992) and Aust and others (1995). In September, 1991, each treatment plot in the two disturbance classes (trafficked skid trail or nontrafficked) received one of the following site preparation treatments: none, disking, bedding, or disking with bedding. Each of these site preparation treatment areas were split into two 20-feet by 40-feet fertilization treatment areas; one of these split plots received no fertilization while the other received 300 pounds per acre of 10-10-10 fertilizer. Loblolly pine seedlings were hand-planted in February 1992.

Measurements

Postharvest and presite preparation measurements were conducted during the spring, summer, and fall of 1990 in order to characterize the soil physical properties within all trafficked and nontrafficked areas prior to site preparation. Detailed descriptions of these measurements and results are provided by Tippett (1992) and Aust and others (1995).

Following site preparation, soil and hydrologic characterizations were conducted in the 1992 growing season and second-year seedling growth was measured in fall 1993 as described by Scheerer (1994) and Scheerer and others (1995). During the late winter of 1996, fourth-year growth measurements were taken. Total tree heights were measured to the nearest 0.05 meter with a height pole, and diameters were measured to the nearest centimeter with diameter tapes. After 4 years, only eight of the original twelve replications remained; four had been compromised by wildfires. Therefore, all data from presite preparation, 2-years after site preparation, and 4-years after site preparation were re-analyzed with only eight replications. All data were analyzed as a split-split plot within a completely randomized block design (Steele and Torrie 1980) as presented in table 1. If significant effects were detected (P-value < 0.1), then a Fishers Protected LSD test was used to separate the means.

Table 1—Generalized analysis of variance table

Source of variance	Degrees of freedom
Replication	7
Traffic	1
Error a	7
Site preparation	3
Site preparation X traffic	3
Error b	42
Fertilization	1
Fertilization X traffic	1
Fertilization X site preparation	3
Fertilization X traffic X site preparation	3
Error c	56
Total (corrected)	127

RESULTS AND DISCUSSION

Effects of Traffic Prior to Site Preparation

The traffic associated with the primary skid trails caused by wet weather harvesting had several effects on the soil physical and hydrologic properties prior to site preparation (table 2). Within the primary skid trails, soil bulk density values were higher and these increases in soil bulk density resulted in reduced soil macropore space. Macropore space is critical for internal soil drainage and aeration of the soil rooting zone (Greacen and Sands 1980). The reduction of macropore space within the trafficked areas was reflected by reduced saturated hydraulic conductivity values within the skid trails and higher water tables below the skid trails (table 2). Overall, the initial effect of the disturbance was to decrease drainage of these poorly drained soils. These results emphasize the need for some type of amelioration for compacted and rutted sites.

Two-Year Effects of Traffic and Site Preparation

Site preparation effects on soil and vegetative properties were evaluated after the second growing season (tables 3 and 4). Site preparation did not significantly affect soil bulk

Table 2—Traffic effects on soil physical and hydrological properties prior to site preparation (Tippett 1992)

Treatment	Bulk density	Macro-pore space	Saturated hydraulic conductivity	Relative water table
	Mg/M^3	*Percent*	*Cm/hour*	*Cm*
Non-trafficked	1.24 b	15.2 b	5.2 a	0.0 a
Trafficked	1.39 a	5.9 a	1.6 b	+18.0 b

Table 3—Traffic and site preparation effects on soil properties 2-years after treatment installation (Scheerer 1994)

Treatment	Bulk density	Macro-pore space	Saturated hydraulic conductivity
	Mg/M^3	*Percent*	*Cm/hour*
Non-trafficked			
None	1.22 a	15.1 c	5.0 c
Disking	1.23 a	12.5 b	0.5 a
Bedding	1.25 a	14.3 c	2.9 bc
Disking and bedding	1.25 a	14.6 c	2.2 b
Trafficked			
None	1.33 b	2.6 a	1.0 a
Disking	1.38 b	2.7 a	0.5 a
Bedding	1.29 b	13.3 bc	1.4 ab
Disking and bedding	1.34 b	9.9 b	0.5 a

Table 4—Traffic and site preparation effects on loblolly pine growth 2 years after treatment installation (treatment values include fertilized and nonfertilized treatment data; Scheerer 1994)

Treatment	Total height	Diameter at breast height[a]
	----*m*----	-------*Cm* ------
Nontrafficked		
None	0.6 bc	0.9 b
Disking	0.5 b	0.9 b
Bedding	0.8 c	1.7 d
Disking and bedding	0.9 c	1.8 d
Trafficked		
None	0.2 a	0.4 a
Disking	0.3 a	0.8 b
Bedding	0.6 bc	1.2 c
Disking and bedding	0.5 b	1.1 c

[a] Includes trees that were too short to have d.b.h. values. Diameter recorded as 0 centimeter for those trees.

density values, but the harvest traffic effects on bulk density were still evident. Overall, trafficked areas had soil bulk density values that were approximately 0.1 megagrams per cubic meter higher than those found in the nontrafficked treatments. The macropore space percentages and saturated hydraulic conductivity values followed the same general trends of bulk density; site preparation did little to restore either of these two soil physical properties (table 3). In fact, the site preparation treatments actually decreased hydraulic conductivity compared to the nontrafficked treatment that received no site preparation. The negative effect of site preparation on saturated hydraulic conductivity was most pronounced on the disking and disking with bedding treatments. The negative effects were less severe on the bedding treatments. Apparently, the disking and disking with bedding treatments reduced soil water movement by interrupting the natural channels of flow, such as old root channels and earthworm burrows.

After 2 growing seasons, the bedding and bedding with disking treatments were effective in partially restoring the diameter and height growth of loblolly pine grown in skid trails (table 4). However, the disking treatment had either no effect or a slightly negative effect on tree growth. Apparently, the interruption of soil water movement within the disked areas was sufficient to negatively affect loblolly pine seedling growth.

Fourth-Year Effect of Traffic and Site Preparation

Four years after the site preparation treatments had been installed, the effects of wet-weather harvest traffic on the growth and survival of loblolly pine were almost totally mitigated by the bedding and bedding with disking treatments (table 5). Growth differences between the nontrafficked and trafficked areas were no longer significant, although the absolute growth values were always greater in the nontrafficked areas. These data appear to indicate that bedding or bedding with disking are effective ameliorative practices for repair of primary skid trails on wet pine flats, at least with respect to the 4-year growth of loblolly pine. However, it is important to recall that these primary skid trails were relatively small and covered less than 10 percent of the total area of each harvested site.

Fertilization enhanced the effects of all site preparation treatments (table 6), but fertilization alone did not mitigate the effects of wet weather trafficking. However, fertilization combined with bedding or bedding with fertilization provided the best overall ameliorative treatment, at least in terms of loblolly pine growth.

CONCLUSIONS

Wet-weather harvesting operations initially increased soil bulk density and decreased soil drainage of skid trails compared to the nontrafficked areas. After 2 growing seasons, the nonsite-prepared skid trails had lower survival percentages and smaller loblolly pines. The disking treatment was totally ineffective for amelioration of soil physical properties for the growth of loblolly pine for several reasons. Disking caused additional consolidation and compaction of the soils, flattened the small amount of existing microrelief, and probably caused further elimination of natural soil drainage channels.

After 2 growing seasons, neither the bedding nor the disking and bedding treatment had totally ameliorated the reduction of pine productivity, but both treatments clearly resulted in a partial amelioration. After 4 growing seasons, bedding or disking with bedding treatments had comparable growth rates in both the trafficked and nontrafficked areas. These results indicate that some type

Table 5—Traffic and site preparation effects on loblolly pine growth 4 years after treatment installation (p-values < 0.05) (treatment values include fertilized and nonfertilized data)

Treatment	Total height	Diameter at breast height[a]	Survival
	Meters	*Centimeters*	*Percent*
Nontrafficked			
None	1.6 a	1.6 a	64 a
Disking	1.5 a	1.2 a	68 a
Bedding	2.7 b	3.4 b	85 b
Disking and bedding	2.5 b	3.1 b	84 b
Trafficked			
None	1.4 a	0.9 a	66 a
Disking	1.5 a	1.1 a	71 a
Bedding	2.5 b	3.0 b	87 b
Disking and bedding	2.3 b	2.7 b	82 b

[a] Includes trees that were too short to have d.b.h. values. Diameter recorded as 0 centimeter for those trees.

Table 6—Traffic, site preparation, and fertilization effects on loblolly pine height, diameter at breast height, and survival at age 4 years

Treatment	Total height	Diameter at breast height[a]	Survival
	---*m*---	-------*Cm*-------	*Percent*
Nontrafficked			
None			
Without fertilizer	1.5 a	1.4 a	59 a
With fertilizer	1.9 ab	1.8 a	69 a
Disking			
Without fertilizer	1.2 a	0.8 a	67 a
With fertilizer	1.7 ab	1.6 a	69 a
Bedding			
Without fertilizer	2.3 b	2.7 b	85 b
With fertilizer	3.0 b	4.1 b	86 b
Disking and bedding			
Without fertilizer	2.3 b	2.8 b	83 b
With fertilizer	2.6 b	3.3 b	87 b
Trafficked			
None			
Without fertilizer	1.3 a	0.9 a	65 a
With fertilizer	1.5 a	1.0 a	67 a
Disking			
Without fertilizer	1.4 a	0.8 a	68 a
With fertilizer	1.6 ab	1.4 a	77 a
Bedding			
Without fertilizer	2.1 ab	2.5 b	87 b
With fertilizer	2.8 b	3.8 b	88 b
Disking and bedding			
Without fertilizer	1.9 ab	2.0 b	76 b
With fertilizer	2.5 b	3.3 b	84 b

of bedding treatment should be considered for similar sites that have been compacted or rutted by wet-weather harvesting. Site preparation of this nature is usually done on industrial lands, but small, private landowners could also benefit. It is important to note that the disking with bedding treatment is more expensive than bedding alone, while it offers no advantages over bedding alone.

The bedding treatment favored the growth of loblolly pine by creating microsites and partially restoring soil water movement, perhaps due to the incorporation of organic matter. Fertilization had a positive effect on loblolly pine growth and survival within all combinations of harvest traffic and site preparation. However, fertilization alone was not totally effective in restoring the productivity of trafficked areas as has sometimes been suggested. The fertilization was most effective in enhancing loblolly pine growth when it was combined with the bedding treatment.

Overall, the bedding and fertilization treatment appeared to ameliorate the effects of wet-weather harvesting within 4 growing seasons. However, it should be noted that these sites had relatively low overall levels of site trafficking (< 10 percent). We speculate that the trees growing within the skid trails have probably developed root systems that were able to exploit adjacent nontrafficked soils. Sites having higher levels of disturbance would probably have slower recovery rates because the roots would not be able to grow out of rutted and compacted areas as quickly.

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LITERATURE CITED

Allen, H.L.; Campbell, R.G. 1988. Wet pine site management in the Southeastern United States. In: Hook, D.D.; McKee, W.H., Jr.; Smith, H.K.; [and others], eds. The ecology and management of wetlands, Vol. 2: Management, use, and value of wetlands. Portland, OR: Timber Press: 173-184.

Aust, W.M.; Tippett, M.D.; Burger, J.A.; McKee, W.H., Jr. 1995. Compaction and rutting during harvest affect better drained soils more than poorly drained soils on wet pine flats. Southern Journal of Applied Forestry. 19(2):72-77.

Aust, W.M.; Reisinger, T.W.; Burger, J.A.; Stokes, B.J. 1993. Soil physical and hydrological changes associated with logging a wet pine flat with wide-tired skidders. Southern Journal of Applied Forestry. 17(1):22-25.

Burger, J.A.; Wimme, K.J.; Stuart, W.B.; Walbridge, T.A. 1989. Site disturbance and machine performance from tree-length skidding with a rubber-tired machine. In: Miller, J.H., comp. Proceedings of the fifth biennial southern silvicultural research conference; 1988 November 1-3; Memphis, TN. Gen. Tech. Rep. SO-74. U.S. Department of Agriculture, Forest Service: 521-525.

Childs, S.W.; Shade, S.P.; Miles, D.W. R.; [and others]. 1989. Soil physical properties: Importance to long-term forest productivity. In: Perry, D.A.; Meurisse, R.; Thomas, B.; [and others], eds. Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Portland,OR: Timber Press: 53-59.

Foil, R.R.; Ralston, C.W. 1967. The establishment and growth of loblolly pine seedlings on compacted soils. Soil Science Society of America Proceedings. 31:565-568.

Gent, J.A.; Ballard, R.; Hassan, A.E. 1983. The impact of harvesting and site preparation on the soil physical properties of lower coastal plain soils. Soil Science Society of America Journal. 47:173-177.

Greacen, E.L.; Sands, R.A. 1980. Compaction of forest soils - a review. Australian Journal of Soil Research. 18:163-189.

Hatchell, G.E. 1981. Site preparation and fertilizer increase pine growth on soils compacted in logging. Southern Journal of Applied Forestry. 5:79-83.

Hatchell, G.E.; Ralston, C.W. 1971. Natural recovery of surface soils disturbed in logging. Tree Planters Notes. 22(2):5-9.

Hatchell, G.E.; Ralston, C.W.; Foil, R.R. 1970. Soil disturbances in logging: effects on soil characteristics and growth of loblolly pine in the Atlantic Coastal Plain. Journal of Forestry. 68:772-775.

Lockaby, B.G.; Vidrine, C.G. 1984. Effect of logging equipment traffic on soil density and growth and survival of young loblolly pine. Southern Journal of Applied Forestry. 8(2):109-112.

McKee, W.H., Jr.; Hatchell, G.E. 1987. Pine growth improvement on logging sites with site preparation and fertilization. In: Phillips, D.R., ed. Proceedings of the fourth biennial southern silvicultural research conference; 1986 November 4-6; Atlanta, GA. Gen. Tech. Rep. SE-42. U.S. Department of Agriculture, Forest Service: 411-418.

Scheerer, G.A. 1994. Mitigation of harvesting disturbances on a forested wetland in the South Carolina lower coastal plain. Blacksburg, VA: Virginia Polytechnic Institute and State University, Department of Forestry, 125 p. M.S. thesis.

Scheerer, G.A.; Aust, W.M.; Burger, J.A.; McKee, W.H., Jr. 1995. Skid trail amelioration following timber harvests on wet pine flats in South Carolina: two-year results. In: Edwards, M.B., comp. Proceedings of the eighth biennial southern silvicultural research conference. 1994 November 1-3; Auburn, AL. Gen. Tech. Rep. SRS-1. U.S. Department of Agriculture, Forest Service: 236-243.

Steele, R.G.D.; Torrie, J.H. 1980. Principles and procedures of statistics: A biometrical approach. 2d ed. New York: McGraw-Hill. 633 p.

Tiarks, A.E.; Haywood, J.D. 1996. Site preparation and fertilization effects on growth of slash pine for two rotations. Soil Science Society of America Journal. 60:1654-1663.

Tippett, M.D. 1992. Impacts of timber harvesting on soil physical properties in wetlands. Blacksburg, VA: Virginia Polytechnic Institute and State University, Department of Forestry. 165 p. M.S. thesis.

USDA Soil Conservation Service. 1980. Soil survey of Berkeley County, SC. 94 p.

Wilhite, L.P.; McKee, W.H., Jr. 1986. Site preparation and phosphorus application alter early growth of loblolly pine. Southern Journal of Applied Forestry. 9(2):103-109.

LOBLOLLY PINE PLANTATION SOIL NITROGEN AND PHOSPHORUS RESPONSE TO CLEARCUT HARVESTING AND SITE PREPARATION TECHNIQUES

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Abstract—Exchangeable nitrogen and extractable phosphorus concentrations were determined monthly over a 59-month period for two South Carolina lower coastal plain soils supporting young loblolly pine (*Pinus taeda* L.) plantations. Both plantations were clearcut harvested (at ages 17 and 20 years) and replicated blocks of five site preparation techniques were installed in each stand after soil sampling had begun. No consistent seasonal pattern or abnormal increases in soil nitrogen or phosphorus were detected following either harvest or site preparation. This lack of response was attributed to the small amount of mineralizable residual biomass left after harvest. Because little mobile nitrogen and phosphorus were released, the harvest and site preparation operations retained these nutrients onsite, which both maintained site productivity and minimized offsite effects.

INTRODUCTION

The response of loblolly pine (*Pinus taeda* L.) to nitrogen and phosphorus fertilization, especially on coastal plain soils, is well researched (Allen 1985, 1987, Wells and Allen 1985). Phosphorus is generally applied at planting while nitrogen, with or without phosphorus, is applied to established stands (McKee and Wilhite 1986, Wells and Allen 1985). There is concern that forest fertilization may be a nonpoint source of nutrients which degrades downstream water quality (Amatya and others 1996, Hughes 1996). Therefore it is desirable to retain as much nitrogen and phosphorus onsite as possible to minimize both the need for fertilization and any downstream impacts.

Loblolly pine ecosystems conserve nutrients onsite by several nutrient cycling mechanisms that are disrupted by harvesting and site preparation (Jorgensen and Wells 1986). The purpose of this research was to test the hypothesis that there will be a measurable release of nitrogen and phosphorus following clearcut harvesting and site preparation by several operational techniques. The approach was to periodically sample the upper soil horizon of two loblolly pine plantations prior to harvest and for several years after stand establishment. The preharvest data provide a baseline control and the postsite preparation data indicate the timing and pattern of any nutrient release.

METHODS

The study design was replicated, randomized, complete blocks established in two South Carolina coastal plain loblolly pine plantations. The Snow Mill plantation was established in 1969 on a poorly drained Bladen loam soil by shearing, raking, and bedding with phosphorus fertilization at planting. Likewise, the Greeleyville plantation was established in 1967 on a somewhat poorly drained Lynchberg sandy loam by shearing, raking, and bedding with phosphorus fertilization at planting. Treatment plots (61 meters by 61 meters with a 15-meter buffer) were installed in a grid pattern in each stand prior to harvest. Plots in each stand were grouped into three blocks by tree height, and site preparation treatments were randomly assigned to plots within blocks. Site preparation treatments included shearing, raking, and bedding (intensive); bedding only (rebed); disking only; burning only; and herbicide spraying of residual trees (chemical). An unharvested control area was retained in each stand. After site preparation, each treatment plot was split and one-half was assigned a release treatment that maintained 75 percent bare ground for the first growing season after planting. The Snow Mill stand was harvested in June 1986 and was site-prepared a year later in July 1987. The Greeleyville stand was harvested in July 1987 and immediately site-prepared in August. Both stands were hand-planted in December 1987 with 1-0, improved, coastal, loblolly pine, seedlings.

This study focused on a subset of site preparation and release treatments rather than sampling all combinations. Three plots in each stand receiving treatments were sampled as summarized in table 1.

A composite soil sample was obtained from each plot by mixing approximately seven 2-centimeter by 15-centimeter soil cores extracted with an Oakfield tube sampler. Samples were taken from the 0- to 15-centimeters depth and 15- to 30-centimeters depth of the new or old beds. The Snow Mill stand was sampled 61 times from February 1986 until October 1992, mostly on a monthly basis.

Table 1—Site preparation and competition release treatments sampled in two study stands

Site preparation	Release treatment	Stands sampled
Intensive	Unreleased	Both
Intensive	Released	Greeleyville (two plots)
Rebed	Unreleased	Both
Chemical	Unreleased	Both
Chemical	Released	Both
Control		Both

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Likewise, Greeleyville sampling began in April 1987 and continued until October 1992, which included 45 sampling periods. Sampling was completed in 1 day and the samples were stored for less than 10 days prior to analysis. Samples taken prior to April 1988 were stored in an unheated basement until analysis. Samples taken between April 1988 and April 1991 were frozen until analysis, and subsequent samples were immediately air-dried. Nitrate and ammonium nitrogen were extracted with 2M KCl, and phosphorus was extracted with the double acid solution. Concentrations were determined colorimetrically. All concentrations were reported in parts per million and data for the two depths were averaged. The sum of nitrate and ammonium nitrogen was considered as available nitrogen. Data analysis was simply plotting phosphorus and nitrogen data against time to detect unusually large releases.

A special set of samples from three plots in the Snow Mill stand was stored by the three methods to determine whether the different storage methods affected nutrient concentrations. Storage method did not affect the nitrogen concentrations of samples from treatment plots, but the ammonium concentrations of samples from control plots were elevated by basement storage. Immediate air-drying elevated the phosphorus concentrations of all samples.

Another factor that might confound data interpretation was rainfall timing. If so, the soil nitrogen content would decrease with increasing amounts of rainfall and will be less with the same amount of rainfall if it occurred just prior to sampling as opposed to occurring 20 to 30 days prior to sampling. To test this, the soil nitrogen and rainfall data were examined for 15 months for the Snow Mill stand and for 13 months for the Greeleyville stand. The highest correlation between soil nitrogen and amount of rainfall in the prior 5 days, 10 days, 15 days, and 30 days had a correlation coefficient of +0.50, indicating a very weak relation.

RESULTS

Control Plots

Because these plots were neither harvested nor site-prepared, data from these plots reflect natural seasonal patterns and the effects of a change in soil sample storage method. Although the test of storage method discussed above indicated that basement storage of samples from control plots elevated nitrogen concentrations, this is not seen in the monthly data from Snow Mill (fig. 1) or Greeleyville. Both stands exhibited a fluctuating soil nitrogen concentration with no seasonal pattern. There was an unexplained increase in the samples from Greeleyville

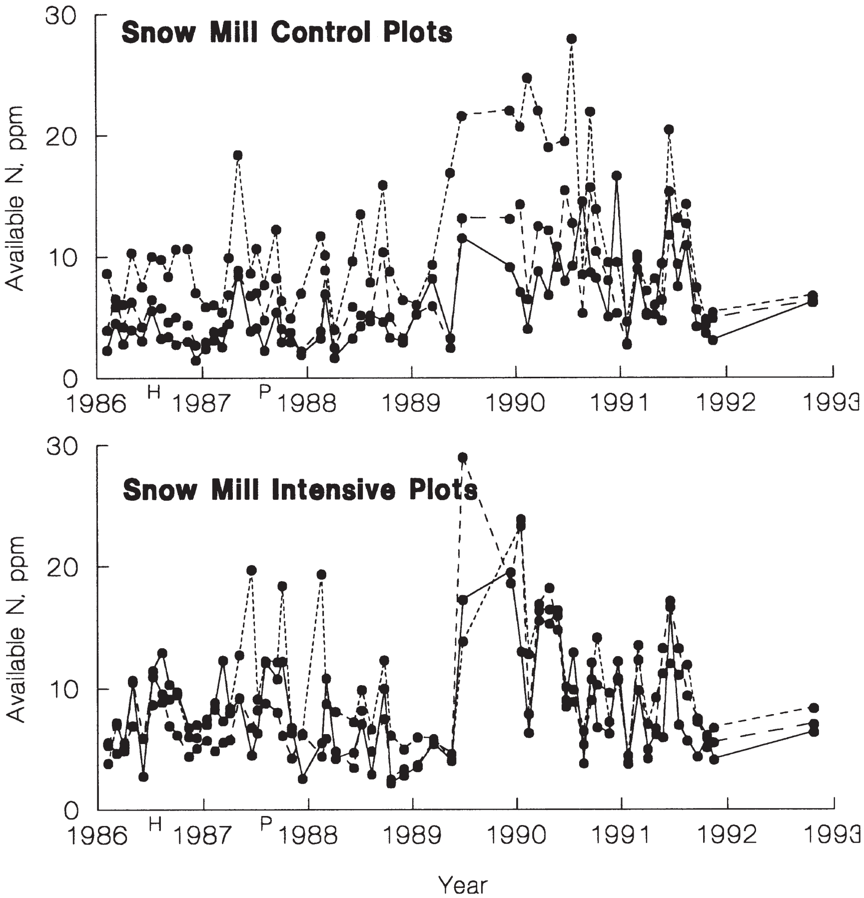

Figure 1—Seasonal pattern of soil-available nitrogen from three control plots (upper) and three intensively site-prepared plots (lower) in the Snow Mill stand. “H” indicates the time of harvest and “P” indicates the time of site preparation.

from June 1989 until June 1990. Likewise the phosphorus data from both stands did not reflect the change in storage methods or any seasonal patterns.

Intensive Site Preparation

Any nitrogen or phosphorus release due to disrupting nutrient cycling mechanisms should be seen in data from plots that were harvested, sheared, raked, and bedded prior to planting. The Snow Mill nitrogen data (fig. 1) indicated a release after both harvest and site preparation and a return to preharvest levels within 3 to 4 months. Greelyville nitrogen data also indicated a release, but this release was delayed for 3 months after site preparation and nitrogen concentrations returned to preharvest levels within 12 months. The Snow Mill phosphorus data did not show a response to harvest or site preparation. The Greeleyville phosphorus data did indicate a release after site preparation, but similar releases occurred many months after disturbance.

Rebed-Only Site Preparation

These plots received far less disturbance than did the intensively site-prepared plots, thus any releases should also be less. The nitrogen data for rebed-only plots were quite similar to the nitrogen data for intensively prepared plots. Snow Mill plots showed an immediate release after both harvest and site preparation with a 3-month recovery. Greelyville rebed-only plots also indicated a release, but it was delayed and recovery was longer, about 12 months. There was no response to disturbance and no discernable seasonal patterns in the phosphorus data from the two stands.

Chemical Site Preparation

Plots receiving the chemical site preparation treatment were the least disturbed because the litter layer and soil were not disturbed by rebedding. In Snow Mill, the response of soil nitrogen was similar to that of the rebed plots, except there was no release after site preparation. In Greeleyville, the response was quite similar to that of the rebed-only plots. Also like the rebed-only plots, the phosphorus data showed no response to harvest, site preparation, or season.

DISCUSSION

These data do not show a major pulse of nitrogen or phosphorus being released in response to harvesting and/or site preparation as was seen in the well-known Hubbard Brook experiment (Bormann and Likens 1970). There are many possible reasons for this including different site, different forest cover, and less destructive treatments. However, the clearcut harvest followed by intensive site preparation was a relatively destructive treatment, yet a release was not detected. I speculate that the lack of release is related to the paucity of material left onsite after harvest that could mineralize and release nutrients.

The preharvest stands were relatively pure loblolly pine plantations, with very few hardwood stems among the pines. After clearcutting, the tracts were clean, open areas. Little biomass was added to the litter layer from harvest because the trees were delimbed at the deck. The only source of mineralizable nitrogen and phosphorus onsite after harvest was the original forest floor, and this was burned after harvest, which may have released nitrogen and phosphorus to the atmosphere as well as to the soil.

Why weren't nutrients released after the residual biomass was incorporated in the soil by the bedding part of site preparation? Again, little organic matter was left onsite to mineralize, and what nutrients were released were probably quickly fixed by the dense grass and sedge cover that developed after site preparation. By the time the grass cover began to die out and release nutrients, the pine seedlings probably had sufficient root biomass to take up these nutrients.

This study clearly shows that loblolly pine plantation re-establishment by clearcut harvesting and intensive site preparation does not release a pulse of nitrogen or phosphorus on the sites studied. The ecosystem and management system used were very nutrient-retentive, providing both onsite and offsite benefits.

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LITERATURE CITED

Allen, H.L. 1985. The value of fertilization as a silvicultural tool. In: (Anonymous) This business of forestry. Proceedings of the third regional technical conference at the 64th annual meeting, Appalachian Society of American Foresters. Raleigh, NC: SAF: 77-86.

Allen, H.L. 1987. Forest fertilization. Journal of Forestry. 85:37-46.

Amatya, D.M.; Gillam, J.W.; Skaggs, R.W.; Blanton, C.D. 1996. Quality of water from drained managed plantations in North Carolina coastal plain. In: Solutions: Proceedings, a technical conference on water quality. Raleigh, NC: North Carolina State University: 130-139.

Bormann, F.H.; Likens, G.E. 1970. The nutrient cycles of an ecosystem. Scientific American. 223:92-101.

Hughes, J.H. 1996. Managed pine forests in coastal North Carolina: a water quality solution? In: Solutions: Proceedings, a technical conference on water quality. Raleigh, NC: North Carolina State University: 56-60.

Jorgensen, J.R.; Wells, C. 1986. Foresters' primer in nutrient cycling. Gen. Tech. Rep. SE-36. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 42 p.

McKee, W.H. Jr.; Wilhite, L.P. 1986. Loblolly pine response to bedding and phosphorus varies by drainage class on lower Atlantic Coastal Plain sites. Southern Journal of Applied Forestry. 10:16-21.

Wells, C.; Allen, L. 1987. Where and when to apply fertilizer. A loblolly pine management guide. Gen. Tech. Rep. SE-36. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 23 p.

RESPONSE OF SOIL BULK DENSITY AND MINERAL NITROGEN TO HARVESTING AND CULTURAL TREATMENTS

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Abstract—The interactive effects of harvest intensity, site preparation, and fertilization on soil compaction and nitrogen mineralization were examined in a loblolly pine (*Pinus taeda* L.) stand growing on a sandy, well-drained soil in eastern Texas. The experimental design was 2 by 2 by 2 factorial, consisting of two harvesting treatments (mechanical whole-treeand hand-fell boles only removed), two site preparation treatments (bedded and unbedded), and two fertilization treatments (fertilized and unfertilized). Soil bulk density was measured before and after harvesting and site preparation. Ion exchange resin bags located at the bottom of soil columns were used to monitor nitrogen mineralization rates in the upper 15 centimeters of soil during the first two growing seasons following harvesting. The mechanical treatment had no effect on soil bulk density at 0 to 5 and 10 to 15 centimeter depths but significantly increased it at 20 to 25 centimeters. Bedding reduced soil bulk density at 10 to 15 and 20 to 25 centimeter depths. The mechanical treatment removed 16 percent more biomass and 127 percent more nitrogen than the hand-fell treatment, but had no affect on nitrogen-mineralization rates. Bedding significantly increased both total mineral nitrogen and nitrate formation during the first growing season but had no effect during the second year. The increase in mineral nitrogen due to the bedded preparation was equal to the increase in mineral nitrogen following application of 250 kilograms per hectare of diammonium phosphate. The results suggest that logging slash and other surface biomass has little influence on nitrogen-mineralization for the first two years after harvesting unless there is considerable soil disturbance and/or incorporation of the surface organic matter.

INTRODUCTION

Declining productivity with successive rotations has been reported for *Pinus radiata* in south Australia (Keeves 1966), *Pinus patula* in Swaziland, Africa (Evans 1978), *Pinus radiata* in New Zealand (Whyte 1973), and *Pinus taeda* and *P. elliottii* in Louisiana, USA (Haywood 1994) raising concerns over the sustainability of current intensive management practices (Powers 1990, Powers and others 1996). In 1989, the USDA Forest Service initiated a series of nationwide studies of long-term soil productivity (LTSP) on the National Forest System (Powers 1990). To complement and extend the LTSP program to industrial forests, a cooperative effort among forest industries, universities, and the U.S. Department of Agriculture was begun in 1993 (Powers and others 1996). This cooperative effort, known as MPEQ for "Monitoring Productivity and Environmental Quality in Southern Pine Plantations," has research installations in four locations in the Southern United States. This is one of the first in a series of reports from this cooperative effort.

Harvesting promotes nutrient losses from forest ecosystems through biomass removal (Kimmins 1977, Tew and others 1986) and increased nutrient mineralization in the soil (Likens and others 1970). Whole-tree harvesting and short rotations accentuate such losses (Switzer and others 1978, Stevens and others 1995). Nitrogen is especially susceptible to losses during harvesting and regeneration (Vitousek and Melillo 1979). Since nitrogen is one of the most limiting factors in many forest ecosystems (Keeney 1980), nitrogen (N) availability is considered an index of soil fertility and soil productivity (Powers 1980). Tew and others (1986) reported that complete-tree harvesting of a 22-year-old loblolly pine (*Pinus taeda* L.) plantation on a Piedmont site in North Carolina removed twice as much N as stem-only harvesting, while Vitousek and Matson (1985) found that harvesting and site preparation increased soil nitrate formation significantly.

Soil compaction caused by harvesting equipment (Guo and Karr 1988, Guo and others 1990) may reduce future forest productivity (Powers and others 1996) unless this compaction is mitigated. Site preparation by bedding improves soil internal drainage increasing survival and/or growth of pine seedlings on poorly drained and moderately well-drained soils (Ducan and Terry 1983, Tiarks 1983, Gent and others 1986, Mckee and Wilhite 1986). On drier sites, bedding can cause moisture stress by channeling water away from seedling root zones (Broeman and others 1983). Mounding and concentrating the surface horizon by bedding could mitigate compaction resulting from harvesting traffic, but the soil disturbance incurred by bedding could also increase nutrient mineralization.

The objectives of the study reported here were to determine the effects of standard operational practices on soil compaction and N availability on a sandy, well-drained soil in the gulf coastal plain of eastern Texas.

MATERIALS AND METHODS

The study site is located in Tyler County, TX, on the property of Temple Inland Forest Products Company. The soil belongs to the Besner series, a coarse-loamy, siliceous, thermic Typic Glossudalf. At time of harvest in August 1994, the site was occupied by a stand of loblolly pine direct-seeded in 1968 and thinned in corridors at age 15 years. There have been at least three harvests of loblolly pines on this site and no history of cultivation. Other characteristics of the stand and soil are shown in table 1.

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Table 1—Characteristics of the loblolly pine plantation at the time of harvesting

Characteristics	Block A	Block B	Block C
Age	26	26	26
Site index (meters, 25 years)	17.1	17.4	17.5
Stand density (stems per hectare)	1962	1625	1805
Basal area (square meters per hectare)			
Pine	29.6	25.1	29.4
Hardwood	2.7	2.3	2.5
Volume[a] (cubic meters per hectare)			
Pine	246.5	221.2	255.8
Hardwood	21.0	21.2	18.9
Overstory biomass[a] (tons per hectare)			
Pine	115.1	101.7	120.7
Hardwood	11.2	11.8	10.1
Understory biomass (tons per hectare)	5.3	12.1	14.0
Litter biomass (tons per hectare)	24.3	17.7	17.5
Soil carbon: 0 to 15 centimeters (pct)	1.075	1.058	1.422
Soil nitrogen: 0 to 15 centimeters (pct)	0.038	0.030	0.045
Soil CEC: 0 to 15 cm (meq per gallon)	0.725	0.688	0.638
Soil pH: 0 to 15 centimeters	4.9	5.0	4.8

[a] Volume and biomass equations for pine from Baldwin (1987),for hardwood from Clark and others (1985).

Prior to harvesting, three experimental blocks were established. Each block was divided into eight 42- by 28-meter (0.12 hectare) plots. On each plot, height and diameter at breast high (d.b.h.) were recorded for all trees > 5 centimeters d.b.h. Four 1- by 2-meter subplots were established in each main plot. All vegetation < 5 centimeters d.b.h. was clipped, weighed, and subsampled for moisture determination and elemental analysis. The litter was also weighed, subsampled, and returned to the laboratory for analysis. Three dominant and codominant pines were felled on each plot for stem analysis. Starting at groundline, a disc was removed every 0.5 meters for 10 meters and every 1 meter from 10 meters to the tip. From the 0-, 5-, and 10-meter discs, a 22.5-degree wedge was removed. Wood and bark were separated, dried, ground, and composited for elemental analysis.

Soil samples for elemental analysis were collected from four locations on each plot at depths of 0 to 10 centimeters, 10 to 20 centimeters, and 20 to 30 centimeters. Soil bulk density was determined in June 1994, 1 month before harvesting, and in May 1995, 9 months after harvesting. Volumetric samples were taken at four locations on each plot at depths of 0 to 5 centimeters; 10 to 15 centimeters; 20 to 25 centimeters. The volumetric samples were dried at 105°C to a constant weight.

Harvesting was conducted July 25 through August 5, 1994. The mechanical whole-tree treatment (MWT) employed a 600 series Hydro-Ax feller-buncher with a rotary cutter and three rubber tire skidders. All merchantable pine (and most unmerchantable pine and hardwoods) were felled, bunched, and skidded to the loading deck where they were delimbed and topped. On the hand-felled boles only (HFB) plots, merchantable pine were felled with chainsaws, delimbed, and topped in place. Merchantable boles were lifted from the plots by a loader positioned outside the plot.

On September 20, 1994, the entire harvested area was treated aerially with a mixture of imazapyr and triclopyr (0.5 plus 2.0 kilograms per hectare). Bedding was performed on October 17 and 18, 1994, with a Savannah stump-jump plow on a D-7 tractor. The site was planted with improved 1-0 loblolly pine seedlings in February 1996. On May 6, 1996, DAP was broadcast by hand.

Nitrogen mineralization was monitored in soil columns enclosed in an uncovered, polyvinyl chloride tube with a package of mixed-bed ion exchange resin (IER) at the bottom (Binkley and Matson 1983, Hart and Binkley 1985). Binkley (1984) suggested this technique was most appropriate for field estimation of both N-mineralization and transport. We further confirmed that no further transformation or removal of NH_4^+ or NO_3^- occurred once adsorbed by the IER.

The 5- by 30-centimeter tubes, beveled on the lower rim, were driven into the soil approximately 15 centimeters and carefully removed. Approximately 1.0 centimeter of soil was removed from the bottom of the tube and replaced with a bag of resin. The tube was then returned to the hole. IER bags contained 8 grams of Fisher No. R276-500 plus a perforated plastic disc about 5.1 centimeters in diameter. Both disc and resin were wrapped in nylon mesh. Bags were assembled and stored frozen until transported to the field in a cooler. Four tubes were placed in each plot. The incubations were conducted May 15, 1995 to November 9, 1995 and May 17, 1996 to November 12, 1996. Resin bags were replaced approximately every 8 weeks during these periods. To determine ambient levels of mineral N, soil samples were collected with a push-tube adjacent to the incubation tubes at the beginning and end of each incubation period.

Mineral N was determined by the same methods for both soil and resin. Ten grams of soil (or 8.0 grams of resin) were placed in 80 mililiters two nitrogen potassium chloride (a 20-gram sample of soil was dried at 105^{o}C for moisture determination). Extractions were shaken at approximately 275 revolutions per minute for an hour, allowed to settle for an hour, filtered, and stored at 4^{o}C until analyzed. Ammonium and nitrate N were determined with Alltech's Ammonia Analyzer system. Net N mineralization was determined by subtracting initial (May) soil mineral-N (NH_4^+ + NO_3^-) from the sum of final (Nov) soil mineral-N plus mineral-N captured by IER bags.

Since fertilizer was not applied until May 6, 1996, the statistical model for the 1995 N-mineralization data was an unbalanced 2 by 2 factorial. Soil bulk density after harvesting and site preparation was subjected to analysis of covariance with bulk density before harvesting as the covariate. Unless indicated otherwise, all significant difference refers to α=0.05.

RESULTS

MWT harvesting did not alter soil bulk density at 0 to 5 centimeters or 10 to 15 centimeters but significantly ($p<0.005$) increased it at 20-25 cm depth (table 2). Bedding did not change soil bulk density in the first 5 centimeters from the surface but reduced it 10 to 15 centimeters ($p<0.001$) and 20 to 25 centimeters ($p<0.001$) soil depths (table 2). However, the crests of the beds were 15 to 30 centimeters above the original soil surface datum. Thus, the stratum at 20 to 25 centimeters from the crest of the beds is not comparable to the stratum sampled at that depth on the unbedded plots. In the near term, bedding appears to have increased the volume of low density soil available for root growth, but a zone of soil compacted during harvesting may still remain.

Assuming all aboveground components of merchantable pine (d.b.h. > 15 centimeters) were removed from the MWT plots while only boles of merchantable pine were removed from the HFB plots, MWT harvesting removed 16 percent more biomass and 127 percent more N than was removed by HFB harvesting (table 3). To verify this assumption, three MWT and three HFB plots were selected and residue biomass determined on the same 1- by 2-meter subplots used in the original biomass sampling. Actual residue differed from estimated residue by less than 5 percent although the coefficient of variations among subplots was quite high.

However, the large differences in nitrogen-rich residue remaining on the HFB plots did not result in a detectable difference in mineral N in the soil during the first two growing seasons following harvest (tables 4 and 5). Conversely, bedded soils were approximately 30 percent higher in mineral N than unbedded soils (table 4). And more mineral N was captured in the resin bags from bedded soil during the May/July monitoring period of the

Table 2—Mean soil bulk density by depth in May 1995 after harvesting in August 1994 and bedding in October 1994 (adjusted by covariance bulk density determined before harvesting)

Harvest method	Not bedded	Bedded	Mean[a]
Soil depth: 0 to 5 centimeters			
Hand fell, boles only	1.11	1.21	1.16a
Mechanical whole tree	1.26	1.19	1.22a
Mean[a]	1.18a	1.20a	
Soil depth: 10 to 15 centimeters			
Hand fell, boles only	1.31	1.17	1.24a
Mechanical whole tree	1.39	1.13	1.26a
Mean[a]	1.35a	1.15b	
Soil depth: 20 to 25 centimeters			
Hand fell, boles only	1.38	1.28	1.33b
Mechanical whole tree	1.49	1.31	1.40a
Mean[a]	1.44a	1.30b	

[a] Means in the same column or row within depths followed by different letters are significantly different ($p<0.05$).

Table 3—Estimated[a] biomass and nitrogen (N) removal by mechanical whole tree (MWT) and hand-fell, boles only (HFB) harvesting based on removal of all pine with d.b.h. > 15 centimeters

Factor measured	MWT	HFB	Difference
			Percent
Total aboveground biomass (tons per hectare)	148	160	-08
Biomass removal (tons per hectare)	92	78	+16
Total aboveground N (kilograms per hectare)	402	462	-13
Nitrogen removal (kilograms per hectare)	134	59	+127

[a] Volume and biomass equations for pine from Baldwin (1987), for hardwood from Clark and others (1985).

Table 4—Ambient mineral N content of upper 15 centimeters of soil in May 1995 after harvesting in August 1994 and bedding in October 1994

	Site preparation		
Harvest method	Not bedded	Bedded	Mean[a]
	-------*Kilograms per hectare*-------		
Hand-fell, boles only	59.8	79.2	69.7a
Mechanical whole tree	65.1	81.1	73.1a
Mean[a]	62.5b	80.2a	

[a] Means within the same column or row followed by different letters are significantly different ($p<0.05$).

first growing season. But after the middle of the first growing season, differences due to bedding were not detected after the July 1995 sampling (table 5).

Application of diammonium phosphate resulted in an increase of 8 to 10 kilograms per hectare mineral N moving through the soil profiles in the sampling tubes, and the increase was consistent across both harvesting and site preparation treatments (table 5). But even with the addition of mineral N fertilizer, the amount of soil mineral N during the second growing season appeared to be below that of the first.

DISCUSSION

Increased soil bulk density at 20 to 25 centimeter depth following mechanical harvesting but not at 0 to 5 or 10 to 15 centimeters was observed on the MPEQ site in north Louisiana as well as in the present study.[2] The relatively high organic matter content of the upper soil strata may offer sufficient resilience to prevent compaction near the surface. Bedding, which produces a ridge of unconsolidated soil and surface organic matter, may mitigate any loss of readily exploitable soil volume caused by compaction at 20 to 25 centimeters. But bedding does not necessarily eliminate this pan or zone of compacted soil below the surface horizons. Since soil compaction may last a decade or more (Wells and Morris 1983, Miller and others 1996), a compacted zone below 20 centimeters may reduce root penetration and productivity later in the rotation.

On the basis of earlier reports (Well and Jorgensen 1978, Vitousek and Matson 1985), we expected the N-rich residues left by HFB harvesting to result in higher net soil N mineralization than MWT. Our data did not support this hypothesis. In the studies of Vitousek and Matson (1985), harvesting was followed by further disturbance of the surface soil by burning, discing, or both. When we disturbed the soil by bedding, we observed increased N mineralization but again no difference between harvesting systems was apparent.

Recently, Wilson (1994) reported a series of studies of N mineralization on the LTSP study plots in eastern North Carolina. Two years after harvesting, he could find no difference in N mineralization rate between organic removal levels ranging from a level comparable to our HFB to a complete removal of all surface organic matter to the mineral soil. Soil compaction, however, significantly reduced N mineralization.

While the amount on N contained in the branches and tops of harvested pine is considerable (table 3), over five times as much is present in the 0 to 15 centimeter layer of mineral soil (table 1). The large amounts of N mineralized during the first growing season (1995) most likely derived from root mortality and other below-ground sources. Differences in surface residue or mechanical traffic between the two harvesting systems did not influence the process. Severing the overstory forest results in a vigorous but rather brief period of N mineralization. Bedding incorporates fresh

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Table 5—Total mineral (NH_4^+ + NO_3^-)captured by ion exchange resin (IER) bags during the first two growing seasons after harvesting and site preparation of a loblolly pine plantation in eastern Texas

	Monitoring Period			
Main treatment[a]	May/ July 95	July/ Sep 95	May/ July 96	July/ Sep 96
	----------------Kilograms per hectare--------------			
Hand-fell, boles only				
No added N	51.6	18.1	16.9	15.4
Added N	—	—	28.5	21.0
Mechanical whole tree				
No added N	52.1	21.0	19.2	13.0
Added N	—	—	24.4	17.3
Not bedded				
No added N	45.1[a]	17.4	17.8	13.2
Added N	—	—	26.7	25.0
Bedded				
No added N	58.4[a]	21.7	18.4	15.3
Added N	—	—	26.2	23.6
Not fertilized	n.a.	n.a.	18.1[a]	14.2[a]
Fertilized	n.a.	n.a.	26.4[a]	24.3[a]

[a] The main effect of bedding was significant ($P<0.05$)for the May/July 95 monitoring period and the main effect of fertilizer was significant ($P<0.05$) for both monitoring periods in 1996. No other main effects or interactions were found to be significant at $P<0.05$.

carbon sources from the surface, increases aeration, severs and macerates root systems to a depth of 10 to 20 centimeters and increases the magnitude but not the duration of the mineralization process.

Continued monitoring to determine the long-term role of surface biomass in maintaining soil organic matter and nutrient richness is a major objective of both LTSP and MPEQ research.

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LITERATURE CITED

Baldwin, V.C., Jr. 1987. Green and dry-weight equations for above-ground components of planted loblolly pine trees in the west Gulf region. Southern Journal of Applied Forestry. 11(4):212-218.

Binkley, D. 1984. Ion exchange resin bags: factors affecting estimates of nitrogen availability. SSSA Journal. 48:1181-1184.

Binkley, D.; Matson, P. 1983. Ion exchange resin bag method for assessing forest soil nitrogen availability. SSSA Journal. 47:1050- 1052.

Broeman, F.S.; Sarigumba, T.I.; Immel, M.J. 1983. Site preparation and slash pine productivity. In: Stone, E.L. ed. Proceedings, Symposium managed slash pine ecosystem, 1981 June 9-11; Gainesville, FL. University of Florida: 131-149.

Clark, A., III; Phillips, D.R.; Frederick, D.J. 1985. Weight, volume, and physical properties of major hardwood species in the Gulf and Atlantic Coastal Plains. Res. Pap. SE-250. Asheville, NC: U.S. Department of Agriculture, Forest Service. 78 p.

Ducan, D.V.; Terry, T.A. 1983. Water management. In: Stone, E.L., ed. Proceedings, Symposium managed slash pine ecosystem, 1981 June 9-11; Gainesville, FL. University of Florida: 91-111.

Evans, J. 1978. A further report on second rotation productivity in the Usutu forest, Swaziland - results of the 1977 reassessment. Comm. For. Rev. 57(4):253-261.

Gent, J.A.; Allen, H.L.; Campbell, R.G.; Wells, C.G. 1986. Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. Southern Journal of Applied Forestry. 10:124-128.

Guo, Y.; Karr, B.L. 1988. Influence of trafficking and soil moisture on bulk density and porosity on Smithdale sandy loam in North- Central Mississippi. In: Proceedings, 5th biennial southern silvicultural research conference; 1988 November 1-3; Memphis, TN: 533-538.

Haywood, J.D. 1994. Early growth reductions in short rotation loblolly pine and slash pine in central Louisiana. Southern Journal of Applied Forestry. 18(1):35-39.

Keeney, D.R. 1980. Prediction of soil nitrogen availability in forest ecosystems: a literature review. Forest Science. 26:159-171.

Keeves, A. 1966. Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the southeast of South Australia. Australian Forestry. 30:52-63.

Kimmins, J.P. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. Forest Ecology and Management. 1:169-183.

Likens, G.E.; Bormann, F.H.; Johnson, N.M.; [and others]. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook ecosystem in New Hampshire. Ecological Monographs. 40:23-47.

McKee, W.H. Jr.; Wilhite, L.P. 1986. Loblolly pine response to bedding and fertilization varies by drainage class on lower Atlantic Coastal Plain sites. Southern Journal of Applied Forestry. 10:16-21.

Miller, R.E.; Scott, W.; Hazard, J.W. 1996. Soil compaction and conifer growth after tractor yarding at three coastal Washington locations. Canadian Journal of Forest Research. 26:225-236.

Power, R.F. 1980. Mineralizable soil nitrogen as an index of nitrogen availability to forest trees. SSSA Journal. 44:1314-1320.

Powers, R.F.; Alban, D.H.; Miller, R.E.; [and others]. 1990. Sustaining site productivity in North American forests: problems and prospects. In: Gessel, S.P.; Lacate, D.S.; Weetman, G.F.; Powers, R.F., eds. Sustained productivity of forest soils. Proceedings, 7th north American forest soils conference; 1988 July 24-28; Vancouver, B.C. University of British Columbia, Faculty of Forestry: 49-79.

Powers, R.F.; Tiarks, A.E.; Burger, J.A.; Carter, M.C. 1996. Sustaining the productivity of planted forests. In: Carter, M.C., ed. Proceedings, 35th Louisiana State University forestry symposium, Growing trees in a greener world: industrial forestry in the 21st century. Louisiana State University, School of Forestry, Wildlife & Fisheries, Agricultural Center, Louisiana Agricultural Experiment Station: 97-134.

Switzer, G.L.; Nelson, L.E.; Hinesley, L.E. 1978. Effects of utilization on nutrient regimes and site productivity. Proceedings, Complete- tree utilization of southern pine; 1978 April; New Orleans, LA. Madison, WI: FPRS.

Tew, D. Thompson; Morris, L.A.; Allen, H. Lee; Wells, C.G. 1986. Estimates of nutrient removal, displacement and loss resulting from harvest and site preparation of a *Pinus taeda* plantation in the Piedmont of North Carolina. Forest Ecology and Management. 15:257-267.

Tiarks, Allan E. 1983. Effect of site preparation and fertilization on slash pine growing on a good site. In: Jones, E.P., Jr., ed. Proceedings, 2nd biennial southern silvicultural research conference; 1982 November 4-5; Atlanta, GA. Gen. Tech. Rep. SE-24. Asheville, NC: SAFES: 34-39.

Vitousek, P.M.; Matson, P.A. 1985. Disturbance, nitrogen availability, and nitrogen losses in an intensively managed loblolly pine plantation. Ecology. 66:1360-1376.

Vitousek, P.M.; Melillo, J.M. 1979. Nitrate losses from disturbed forests: patterns and mechanisms. Forest Science. 25:605-619.

Wells, C.G.; Jorgensen, J.R. 1978. Nutrient cycling in loblolly pine: silvicultural implications. Tappi. 61:29-32.

Whyte, A.G.D. 1973. Productivity of first and second crops of *Pinus radiata* on the Moutere gravel soils of Nelson. New Zealand Journal of Forestry. 1973:87-103.

Wilson, C.A. 1994. The effects of compaction and organic matter removal on nitrogen mineralization in a coastal plain soil of North Carolina. Raleigh, NC: North Carolina State University. 31 p. M.A. thesis.

SOIL STRENGTH, VOLUMETRIC WATER CONTENT, AND SOIL ROUGHNESS CHARACTERISTICS OF A BEDDED WET PINE FLAT

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Abstract—Harvest operations conducted under high soil moisture conditions often result in highly disturbed areas. Strategies adopted to avoid a high degree of site disturbance from harvesting can include harvesting under low moisture conditions or utilization of site preparation techniques. However, in this study we found that harvesting under low moisture conditions increased soil strength. Bedding is able to reduce soil strength and lower volumetric water content in both harvest conditions. Bedding increases surface roughness in harvested sites and elevates local topography. Low moisture conditions resulted in a higher degree of surface roughness resulting in greater bed height. No differences were detected in first-year loblolly pine survival for harvested or bedded treatments, but long-term assessments are necessary to truly investigate the relationship between bed characteristics and loblolly growth.

INTRODUCTION

Forest harvest operations conducted on wet pine flats result in surface soil disturbances that have been classified as compacted, rutted, and puddled (Burger and others 1989). The type and degree of disturbance varies with soil moisture content and a greater susceptibility to disturbance occurs as soil moisture content increases (Aust and others 1993, Burger and others 1989, Burger and others 1995). Soil physical properties that are altered in disturbed sites include bulk density, soil strength, hydraulic conductivity, porosity, and soil moisture content (Aust and others 1993, Aust and others 1995). The net result of these impacts is lowered site productivity.

Site productivity can be enhanced on wet pine flats through site preparation prior to planting, especially by bedding. Bedding reduces soil moisture content, improves soil aeration, lessens impacts to soil physical properties, and provides roughness on the soil surface (Gent and others 1983, Pritchett 1978, Terry and Campbell 1981). Improvements in the productivity of loblolly (*Pinus taeda*) and slash (*P. elliottii* Engelm.) pine have occurred in bedded wet pine flats, especially on poorly and very poorly drained soils (Cain 1978, Gent and others 1986, Wilhite and Jones 1981). However, information is not available on soil physical properties of bedded sites, the influence of site conditions on bed characteristics, and/or the relationship between soil physical properties of beds and pine productivity.

The objective of this study was to evaluate bedded surfaces of a wet pine flat for soil roughness, soil strength, volumetric water content, and loblolly pine survival to determine whether differences due to harvesting conditions (moisture levels of wet and dry) and site preparation (bedding and mole plowing/bedding) exist, and the impact on first-year survival of loblolly pine.

METHODS

Study Site

The study site was located on the lower coastal plain of South Carolina on an area of low elevations of marine and fluvial deposits. The stand was a 20-year-old loblolly pine stand owned and managed by Westvaco Corporation of Summerville, SC. The understory consisted of red maple (*Acer rubrum*), water oak (*Quercus nigra*), willow oak (*Q. phellos*), cherrybark oak (*Q. falcata* var. *pagodifolia*), sweetgum (*Liquidamber styraciflua*), and palmetto (*Sabal sp.*). Soils within the study site were members of the Alfisol, Mollisol, and Ultisol orders.

Treatments

The experimental design consisted of a randomized complete block assessing the impact of harvesting under two moisture levels (high moisture vs. low moisture) and two methods of site preparation (bedding and mole plowing/bedding) on soil strength, soil roughness, and volumetric water content, replicated three times. Treatment combinations consisted of wet harvesting and no site preparation (flat planting) (WFP), wet harvesting and bedding (WB), wet harvesting and mole plowing/bedding (WMB), dry harvesting and no site preparation (flat planting) (DFP), and dry harvesting and bedding (DB) as well as an undisturbed control (CON) area in all blocks. The entire study area encompassed 57.6 hectares subdivided into three blocks, each approximately 19.2 hectares in size and further subdivided into six treatment plots of 3.2 hectares. Volumetric water contents of 30 and 12 percent corresponded to soil moisture content at the time of wet harvesting and dry harvesting, respectively. Site preparation was conducted at an average soil moisture content of approximately 45 percent.

Soil Measurements

The site was assessed after harvest operations for the occurrence of site disturbances and classified according to preselected disturbance classes: compressed soil, ruts less than 0.2 meters, ruts greater than 0.2 meters, and churned soils. Site preparation activities were initiated and

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completed in fall 1995 and hand-planting of seedlings completed in January 1996. Five disturbance classes were mapped in wet harvested sites and two disturbance classes were mapped in dry harvested sites. The percentage of disturbance in each harvest treatment was calculated by summing the mean percentages of each disturbance class; this consisted of four disturbance classes in wet harvested treatments and one in dry harvested treatments.

Soil roughness estimates were made by placing a chain approximately 6.1 meters in length over the exposed soil surface and fitting the chain to the contours of the soil surface fully extending each link and measuring the distance between the origin and its endpoint (Saleh, 1991). A ratio of fitted length to horizontal length was calculated and termed the roughness coefficient, RC. A logging chain was chosen for the estimation of RC rather than a roller chain due to distances between beds and site conditions. Soil strength was determined with a Rimik CP20 recording cone penetrometer with a base cone diameter of 113.0 square millimeters, manually inserted to a depth of 0.50 meters and recorded in 0.025 meter increments in accordance with ASAE standards (ASAE 1992). The required force divided by the cross sectional area of the base of the cone gives cone index (CI) in units of pressure (Megapascals). Volumetric water content was determined by Time Domain Reflectometry (TDR) at soil depths of 0.0 to 0.15, 0.0 to 0.30, and 0.0 to 0.45 meters, using standard rod lengths corresponding to previous depth increments, and volumetric water content estimated for the depth increments of 0.0 to 0.15, 0.15 to 0.30, and 0.30 to 0.45 meters according to Topp and others (1982). Statistical analyses were conducted with the Statistical Analysis System.

RESULTS AND DISCUSSION

Site Disturbances

A higher percentage of site disturbance occurred during harvest operations under high moisture conditions (WFP) compared to low moisture conditions (DFP) (table 1). Site disturbances often exceeded 75 percent in WFP compared to less than 10 percent in DFP. Other studies have found greater levels of disturbance under high moisture conditions and attributed disturbance to lowered soil strength that resulted in compaction, rutting, and puddling upon trafficking (Burger and others 1995).

Soil Response to Harvesting

Soil strength, or cone index (CI), generally increased at all depths in response to harvesting in comparison to its undisturbed state (CON) (table 2). Soil moisture status influenced the degree of change in soil strength as CI values were consistently higher in DFP compared to WFP at comparable depths (table 2). Differences in soil strength in this study due to moisture status were similar to results reported by Murosky and Hassan (1991) for soil surface layers of a wet pine flat in Louisiana. The results of this study and others underscores the influence of soil moisture status at the time of harvesting on resulting impacts associated with harvesting.

Volumetric water contents (VWC) of 0.40 centimeters per cubic centimeter and higher were noted for each depth in each treatment (table 2). Elevated VWC may have resulted from the impact of harvest traffic on soil physical structure by increasing bulk density and reducing pore space which simultaneously increased VWC and lowered soil strength (Burger and others 1989). Since there is an inverse relationship between CI and VWC, the elevated VWC may have masked more significant differences in CI between treatments.

Effect of Bedding Treatment

Site preparation of wet pine flats primarily consists of bedding, but some benefit may be derived by mole plowing in conjunction with bedding. Mole plowing is employed in sites of high clay content and water saturation to reduce the depth of the water table (Robinson and others 1987). Site preparation of wet harvested treatments reduced CI and VWC from initial harvested (WFP) and undisturbed (CON) site conditions (table 2). Little difference was detected for CI and VWC between site preparation methods on wet harvested sites. Mole plowing reduced VWC at all depths but CI remained similar to WB at all depths.

Site preparation in dry harvested treatments was limited to bedding alone (DB). Reductions in CI and VWC in

Table 1—Percent disturbance of each treatment block after harvest prior to the application of site preparation treatments

	Percent disturbance	
Condition/treatment	Undisturbed	Disturbed
High moisture	9.2	90.8
Low moisture	96.2	3.8
Wet harvesting and mole plowing/bedding	20.5	79.5
Wet harvest/bedding	15.7	84.3
Bedding alone	89.8	10.2

Table 2—Cone index and volumetric water content of selected soil depths (0 to 15, 15 to 30, and 30 to 5 centimeters) in a wet pine flat after harvest and site preparation, South Carolina

Treatment	Depth	Cone index	Volumetric water content
	cm	*MPa*	*cm/cm³*
CON	0.15	0.518	0.360
	0.30	1.134	0.356
	0.45	1.157	0.436
WFP	0.15	0.625	0.473
	0.30	1.030	0.399
	0.45	1.350	0.453
DFP	0.15	0.912	0.439
	0.30	1.182	0.403
	0.45	1.376	0.422
WMB	0.15	0.351	0.325
	0.30	0.627	0.346
	0.45	1.164	0.337
WB	0.15	0.358	0.334
	0.30	0.659	0.359
	0.45	1.143	0.450
DB	0.15	0.377	0.273
	0.30	0.556	0.392
	0.45	0.920	0.424

response to bedding were noted from initial site (DFP) and undisturbed (CON) conditions (table 2).

Relative differences in soil strength between preharvest and postharvest conditions were greater for dry harvested sites than for wet harvested sites. Soil strength in DB was approximately 2 times lower than WMB or WB after bedding of the original harvest surface (table 2). One consistent result observed in all bedded treatments was a greater change in intermediate soil layers from the initial harvest conditions to bedded conditions.

Volumetric water content was reduced by bedding of each treatment, with the highest reductions in VWC in surface soil layers. Volumetric water content also decreased in subsoil layers with greater reductions in the subsoil of wet harvested treatments, especially where mole plowing was implemented.

From this study the benefits of bedding are evidenced from the reductions in soil strength and volumetric water content. Bedding enhances survival and growth of pines on harvested sites and is applied extensively in poorly drained sites of the coastal plain (Allen and others 1990). Its utility may be limited in sandy soils but significant improvements may occur in soils with significant clay content (Allen and others 1990, Haines and others 1975). At the present time, the benefit of bedding exists in the early stages of pine growth but more long-term investigations are necessary to fully assess the relationship between bed quality and pine productivity.

Soil Roughness

Soil roughness coefficients (RC) may range from 0 to 1 where 1 is indicative of a flat, or undisturbed, soil surface. Soil roughness coefficients were higher in harvested sites (WFP and DFP) as a result of less surface disturbance (table 3). The formation of beds on harvested sites elevated the soil surface and increased surface relief, which resulted in lower RC values. Roughness coefficients were significantly higher in bedded treatments compared to flat planted treatments, as expected. A comparison of bedded treatments indicated RC was significantly lower (P = 0.10) in DB compared to WB and WMB. Soil roughness would then be expected to be greater in dry harvested sites.

Bedding increases surface roughness by elevating the soil surface to a specific height above the harvested surface. Bedding of dry harvested treatments increased surface roughness, indicating the importance of moisture condition at the time of bedding. Soil moisture status was a significant factor in increasing soil roughness on agricultural soils and was maintained for extended periods when roughness was created under low moisture conditions (Allmaras and others 1967, Lehrsch and others 1987). Pine productivity was enhanced in a sandy soil in Florida as a result of higher beds (Outcalt 1984), which further underscores the importance of proper bedding. Future pine productivity on these sites may benefit from bedding under low moisture conditions.

Loblolly Pine Survival

An examination of first year survival of loblolly pine did not indicate any direct benefits from bedding of harvested sites (table 4). Future assessments of tree growth and survival will be necessary to identify specific characteristics that determine pine productivity.

Table 3—Mean roughness coefficients of a wet pine flat subjected to harvest disturbance under two moisture conditions and two methods of site preparation, South Carolina

Condition/treatment	Roughn	
coefficient		
High moisture condition	0.824 b [a]	
Low moisture condition	0.851 b	
Wet harvesting and mole plowing/bedding	0.769 a	a [/b]
Wet harvesting/bedding	0.770 a	a
Bedding alone	0.748 a	b

Table 4—First-year loblolly pine survival in a wet pine flat in response to harvesting under two moisture conditions and two methods of site preparation, South Carolina (data provided by W.M. Aust)

Condition/treatment	Survival rate
	Percent
High moisture condition	87.6 [a]
Low moisture condition	86.3
Wet harvesting and mole plowing/bedding	86.8
Wet harvesting/bedding	83.9
Bedding alone	81.8

[a] Mean comparison among percent survival (log transformation) were not significantly different from each other at the P = 0.05 level.

CONCLUSIONS

Soil moisture status affected the occurrence of site disturbances on a wet pine flat with higher soil moisture contributing to a higher degree of soil disturbance. Soil strength and volumetric water content increased in response to harvest traffic under both low and high moisture conditions compared to undisturbed conditions. Higher soil strength was associated with harvest traffic under low moisture conditions. Bedding reduced soil strength and volumetric water content under high and low moisture conditions. However, the greater reductions in CI occurred in dry harvested treatments, while the highest volumetric water content reductions occurred in wet harvested treatments. Bedding increased surface roughness in both treatments but significantly more roughness was associated with low moisture conditions.

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LITERATURE CITED

Allen, H.L.; Dougherty, P.M.; Campbell, R.G. 1990. Manipulation of water and nutrients-Practice and opportunity in southern U.S. pine forests. Forest Ecology and Management. 30:437-453.

Allmaras, R.R.; Burwell,R.E.; Holt, R.F. 1967. Plow layer porosity and surface roughness from tillage as affected by initial porosity and soil moisture at tillage time. Soil Science Society of America Journal. 31:550-556.

American Society of Agricultural Engineers. 1992. Soil cone penetrometer. ASAE standard S313.2: 567.

Aust, W.M.; Reisinger, T.W.; Burger,J.A.; Stokes, B.J. 1993. Soil physical and hydrological changes associated with logging a wet pine flat with wide-tired skidders. Southern Journal of Applied Forestry. 17:22-25.

Aust, W.M.; Tippett, M.D.; Burger, J.A.; McKee, W.H., Jr. 1995. Compaction and rutting during harvesting affects better drained soils more than poorly drained soils on a wet pine flat. Southern Journal of Applied Forestry. 19:72-75.

Burger, J.A.; Wimme, K.J.; Stuart, W.B.; Waldridge, T.A., Jr. 1989. Site disturbance and machine performance from tree length skidding with a rubber tire machine. In: Miller, J., ed. Proceedings of 5th biennial southern silvicultural research conference; 1988 November 1-3; Memphis, TN. Gen. Tech. Rep. SO-74. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 521-525.

Burger, M.A.; Aust, W.M.; Patterson, S. 1995. A preliminary wetland trafficability hazard index based on soil moisture. In: Edwards, M.B., ed. Proceedings of the 8th biennial southern silvicultural research conference; 1994 November 1 -3; Auburn, AL. Gen Tech. Rep. SRS-1. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 225-227.

Cain, M.D. 1978. Planted loblolly and slash pine response to bedding and flat disking on a poorly drained site - an update. Res. Note SO- 237. U.S. Department of Agriculture, Forest Service: 6.

Gent, J.A., Jr.; Allen, H.L.; Campbell, R.G.; Wells, C.G. 1986. Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. Southern Journal of Applied Forestry. 10:124-128.

Gent, J.A., Jr.; Ballard, R.; Hassan, A.E. 1983. The impact of harvesting and site preparation on soil physical properties of lower Coastal Plain forest soils. Soil Science Society of America Journal. 47:595-598.

Haines, L.W.; Maki, T.E.; Sanderford, S.G. 1975. The effect of mechanical site preparation treatments on soil productivity and tree (*Pinus taeda* L. and *P. elliottii* Engelm. var *elliottii*) growth. In: Bernie, B.; Winget, C.H., ed. Forest soils and forest land management. Quebec City: Laval University Press: 379-395.

Lehrsch, G.A.; Whisler, F.D.; Romkens, M.J.M. 1987. Soil surface roughness as influenced by selected soil physical properties. Soil Tillage and Research. 10:197-212.

Murosky, D.L.; Hassan, A.E. 1991. Impact of tracked and rubber-tired skidder traffic on a wetland site in Mississippi. Transactions of the American Society of Agricultural Engineers. 34:332-327.

Outcalt, K.W. 1984. Influence of bed height on the growth of slash and loblolly pine on a Leon fine sand in northeast Florida. Southern Journal of Applied Forestry. 8:29-31.

Pritchett, W.L. 1978. Site preparation and fertilization of slash pine on a wet savanna soil. Southern Journal of Applied Forestry. 3:86-90.

Robinson, M.; Mulqueen, J; Burke, W. 1987. On flows from a clay soil-seasonal changes and the effect of mole drainage. Journal of Hydrology. 91:339-350.

Saleh, A. 1991. Soil roughness measurement: chain method. Journal of Soil and Water Conservation. 48:527-529.

Terry, T.A.; Campbell, R.G. 1981. Soil management considerations in intensive forest management. In: Forest regeneration proceedings symposium for engineering systems in forest regeneration. St. Joseph, MI: American Society of Agricultural Engineers: 98-106.

Topp, G.C.; Davis, J.L.; Annan, A.P. 1982. Electromagnetic determination of soil water content using TDR: I. Applications to wetting fronts and steep gradients. Soil Science Society of America Journal. 46:672-678.

Wilhite, L.P.; Jones, E.P., Jr. 1981. Bedding effects in maturing slash pine stands. Southern Journal of Applied Forestry. 5:24-27.