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Influence of Surface and Subsurface Tillage on Soil Physical Properties and Soil/Plant Relationships of Planted Loblolly

Final Report – 07/31/1997 – 07/31/1999

D. L. Kelting
H. L. Allen

May 2000

Work Performed Under Contract No. DE-FC07-97ID13545

For
U.S. Department of Energy
Assistant Secretary for
Environmental Management
Washington, DC

By
North Carolina State University
Raleigh, NC

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RECIPIENT: DEPARTMENT OF FORESTRY, NORTH CAROLINA STATE UNIVERSITY

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FOREWORD

This final technical report presents results from the DOE sponsored project "Influence of Surface and Subsurface Tillage on Soil Physical Properties and Soil / Plant Relationships of Planted Loblolly Pine".

Methodologies for sampling and analyzing soil physical properties were developed by Steve Colbert and Cheryl Stewart with assistance from Ellis Edwards and Keith Cassel (NCSU Soil Science Dept.). Many former NCSFNC staff and graduate students, including Dave Blevins, Steve Colbert, Mark Bost, Robert Ross, Geoff Schaeffer-Harris, and Jean Wilson performed field sampling. Champion International provided additional field assistance. Steve Colbert and Jean Wilson performed most laboratory determinations of air-filled porosity, bulk density, and soil moisture with assistance from Josh Baldwin, Tom Barrett, Martha Brewster, Geoff Schaeffer-Harris, Michele Kaczmarek, and Heather Ramsay. The contributions of these individuals, especially Steve Colbert, is gratefully acknowledged.

The statistical analyses and results presented in this report were prepared by Dan Kelting, with assistance in the interpretation and presentation of results provided by Lee Allen.

This project was supported by a research grant from the Department of Energy / Agenda 2020 program (Identification Number: DE-FC07-97ID13545).

ABSTRACT

Soil tillage can improve tree survival and growth by reducing competing vegetation, increasing nutrient availability, improving planting quality, and improving soil physical properties. We conducted a tillage study with competition control and nutrient amendments to isolate the physical effects of tillage on tree growth. The objectives of this study were to understand: (i) how tillage affects soil physical properties; (ii) the relationships between these properties and root growth; (iii) linkages between root growth response and aboveground growth; and (iv) tillage effects on aboveground growth. Four replicates of a 2 x 2 factorial combination of surface (disking) and subsurface (subsoiling) were installed on a well-drained, clay-textured subsoil, soil located on the Piedmont of North Carolina. Disking improved soil physical properties (reduced bulk density and increased aeration porosity) in the surface 20-cm of soil. Subsoiling improved soil physical properties at all depths in the planting row, with improvements still noted at 60-cm from the planting row in the surface 10-cm of soil. Rooting patterns followed the changes in soil physical properties. Subsoiling resulted in more roots at depth (70 to 80 cm), while no roots were observed below 50 cm with disking. The subsoiling+disking treatment resulted in a negative interaction for soil physical properties and rooting patterns, with effects being intermediate between subsoiling or disking alone. Despite improvements in soil physical properties and changes in rooting patterns, aboveground tree growth was not affected by tillage. Average two-year-old tree height and groundline diameter were 79 and 2.45 cm, respectively, for the control. Physiological measurements indicated that there were no treatment effects on predawn water potential or light saturated photosynthesis, indicating that the trees did not experience any soil water limitations. Measured soil water availability and predicted soil strength corroborated these results, showing that available water and soil strength probably did not limit tree growth on this site. The results of this study point to the need for better diagnostics for identifying sites were tillage is appropriate in situations where fertilization and vegetation control are planned. Potential factors to consider are presence and abundance of old root channels, soil shrink / swell capacity, soil structure, presence and depth to root restricting layers, and historical precipitation records.

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INTRODUCTION

Site preparation is an integral part of the southern pine regeneration system due to its demonstrated efficacy for improving conditions for planting, seedling survival and growth, and stand uniformity. Whether accomplished by burning, herbicides, or tillage, site preparation can reduce levels of competing vegetation, improve resource availability, expose mineral soil for planting, and dispose of debris to facilitate access. Increases in pine productivity attributable to vegetation control or increased nutrient availability via fertilization are reasonably well understood (e.g., Allen et al., 1990; Neary et al., 1990; Jokela et al., 1991; Minogue et al., 1991). However, uncertainty exists concerning the direct effects of surface and subsurface tillage on improving soil physical properties and, consequently, seedling survival and growth (Morris and Lowery, 1988). That is, what added or synergistic benefits can be achieved by tillage beyond those already documented for vegetation control and fertilization?

The benefits of using tillage to ameliorate soil physical properties degraded by compaction due to heavy equipment are well documented (Greacen and Sands, 1980). A considerable amount of research has been done to understand the ability of tillage to improve tree growth, particularly on the use of bedding to improve soil aeration on poorly-drained soils. However, studies are typically confounded by tillage effects on nutrient supply and competing vegetation, two factors well-managed by fertilizers and herbicides. So the additional benefits of tillage on improving soil physical properties for tree growth are largely unknown.

The effects of tillage treatments such as disking and bedding are confined to surface soil horizons, while subsoiling affects both surface and subsurface horizons. Subsoiling has recently received increased interest as it can substantially improve deep root development Berry, 1987) and thereby reduce water stress during dry periods (e.g., Campbell et al., 1974; Kamprath et al., 1979). Total available water storage may also be increased by subsoiling through increasing infiltration of slowly-permeable layers (Morris and Lowery, 1988).

Opportunities may exist for improving the survival and growth of planted pines on a variety of sites, including those characterized by poorly-structured clay and hardpan soils and cemented spodic horizons. Judicious application of tillage technology to realize potential increases in pine productivity will require improved understanding of the mechanisms affecting soil and vegetation response to surface and subsurface treatments, and identification of the appropriate soil and site conditions necessary for maximum gains.

Members of the North Carolina State Forest Nutrition Cooperative (NCSFNC) have established 15 installations of a regional field trial (Regionwide 16) to examine the effects of surface and subsurface tillage on survival and growth of loblolly pine. Each study is located on a uniform soil type within a pre-defined matrix of subsoil texture (sandy loam to clay) and drainage class (well to very poorly). The matrix in soil / site properties will hopefully allow us to identify the soil / site types where tree growth will respond to tillage. The objectives of this project were to understand: (i) how tillage affects soil physical properties; (ii) the relationship between these properties and root growth; (iii) linkages between root growth response and aboveground growth; and (iv) tillage effects on aboveground growth. To accomplish these objectives we conducted a detailed soil and tree growth study at an installation of the Regionwide 16 that we hypothesized would be very responsive to tillage.

MATERIALS AND METHODS

Study Site Description and Land Use History

The experiment was conducted on the Piedmont physiographic province, in Halifax County, North Carolina ($36^0$15′ N $77^0$59′ W) on land owned by Champion International Corporation. The landscape is gently rolling, with an average elevation of 70 m above mean sea level. Historical climate records obtained from Arcola, North Carolina, a National Climate Data Center (NCDC) cooperative weather station located approximately 6 km from the study site, provide an excellent source of local climate data. The growing season varies from 200 to 220 days per year. The 49-year average daily air temperature is 14^0C, and ranges from a low of 3 to a high of 25^0C in January and July, respectively. Over the same time period, total annual precipitation has averaged 1177 mm, and has varied from 1027 to 1320 mm. Average monthly precipitation varies from 82 to 130 mm, with the highest monthly rainfall occurring in July and August.

The study site is comprised of well-drained Tatum and Badin series soils. Both of these soils are Fine, mixed, semiactive, thermic Typic Hapludults (Soil Survey Staff, 1998) formed in residuum from sericite schist, phyllite, or other fine-grained metamorphic rocks. Badin soils have a paralithic contact at 50- to 100-cm depth, while Tatum soils are deeper to bedrock. These soils have moderate shrink-swell potential in the subsoil (>15-cm depth). These soils occur on ridgetops and sideslopes of the Carolina Slate Belt in Piedmont uplands, and are representative of about 35 % of soils found in this region (Daniels et al., 1999).

We have no land-use records prior to the early 1960s, but it is most probable that the land had been under shifting row-crop agriculture from the early 1800s through the early 1900s then abandoned and allowed to develop into an old-field pine stand (Skeen et al., 1993). The land was acquired by forest industry in the early 1960s and converted into plantation with the establishment of a first rotation loblolly pine plantation in 1968. This first plantation was established with mechanical site preparation using a rolling drum chopper followed by hand-planting on 3- by 1.8-m spacing.

Experimental Design and Treatment Description

The study consisted of 4 replicates of a 2 by 2 factorial of surface and subsurface tillage arranged in a randomized complete block design. The treatments were arranged in blocks that achieved maximum within-block uniformity in total height of trees in the previous stand and depth to the argillic horizon. Treatment plots were laid out prior to harvest, and the harvest plan was designed to minimize compaction within plots due to harvesting equipment.

The 1968 plantation was harvested in early April, 1995. The area was chemically site prepared in late July, 1996, using a combination of 3.78 L Accord, 0.36 L Arsenal, and 0.95 L Entry, allowed to brown-up, and then burned. The soil tillage treatments were installed in October, 1996. The surface tillage treatment was installed using a ROME™ disk harrow equipped with 80-cm offset disks. Subsurface tillage was performed using a Savannah™ 310 combination plow (3-in-1 plow) equipped with a 122-cm diameter coulter followed by a winged subsoiler with a 30-cm wide wing set to operate at 50-cm deep. The opposing disks used to form beds with the combination plow were not used. The subsurface plus surface tillage treatment was installed as a two-pass operation with subsurface tillage preceding surface tillage. A Caterpillar™ D7 tractor was used as the prime mover for installing the tillage treatments. The tillage treatments were installed when the volumetric moisture content (%) in the subsoil was just below the plastic limit (PL), corresponding with the optimum moisture content for maximum subsoil fracture (Spoor and Godwin, 1978).

The plots were hand-planted in late March, 1997, with genetically improved 1-0 loblolly pine seedlings in rows spaced 2.7 m apart, with seedlings planted at 2.1 m within rows. The treatment plots consisted of 14 rows by 14 trees (0.11 ha). The middle 8 rows x 6 trees (0.03 ha) were delineated as the measurement plot, leaving an 8.1 by 8.4 m treated buffer distance around the measurement plot. The treated buffer should be sufficient to ensure that the majority of roots originating from trees in the measurement plots are bathed in the treatment for several years.

Soil tillage effects on physical factors were isolated from nutrition and competition factors by applying fertilizer and competition control across all treatments. All plots received the equivalent of 200 kg ha^{-1} diammonium phosphate (DAP) in April, 1998, one year after planting. Fertilizer was hand applied in 0.9-m bands on either side of the planting row (total band width of 1.8 m). Competing vegetation has been controlled annually to achieve a uniform amount of competing vegetation in all plots during the first two growing seasons.

Soil Sampling and Analysis

Undisturbed soil cores 7.6-cm diam by 60-cm length were collected in October 1997 using a Ruark Sampler (Ruark, 1985). Soil cores were obtained between adjacent trees at 0, 30, and 60 cm perpendicular to the planted row at three locations in each measurement plot, for a total of nine soil cores from each plot. The cores were sealed on each end and stored in a refrigerator until laboratory analysis could begin.

Each core was sectioned into 10-cm segments corresponding to the 0- to 10-cm, 10- to 20-cm, 20- to 30-cm, 30- to 40-cm, 40- to 50-cm, and 50- to 60-cm soil depths. The bulk density of each core was determined by weighing the field-moist core segments and using the oven-dried water content determined from loose soil samples, which were collected from the surrounding soil at the same time.

The core segments were set in shallow pans of water and allowed to saturate from below. A low pressure water release apparatus (Cassell and Klute, 1986) was used to determine soil water retention at soil water potentials of 0, -0.98, -4.90, -19.61, and –39.22 kPa. Smaller subsamples were obtained from the cores after the low pressure release work was completed and used to determine soil water retention at soil water potentials of –98, -490, and –1470 kPa using a pressure-plate apparatus (Klute, 1986). These data were used to develop soil water release curves. The water release curves were used to calculate soil physical properties with potentially important effects on root growth and available water.

Soil particle size distributions were determined from the loose soil samples using the hydrometer method (Gee and Bauder, 1986).

Greenhouse studies have shown that in rigid media roots cannot grow through pores less than 140 µm in diameter (Taylor, 1974). We defined soil pore volume greater than 140 µm as an index of rootability called 'rooting volume', with the realization that soil is a semi-rigid system, with it's rigidity defined by interactions between soil texture, organic matter content, and water content.

Aboveground Tree Sampling

Survival was determined after the first growing season. Total height of each seedling was measured during the dormant season following the first and second growing seasons. Groundline diameter measurements were collected during the dormant season following the second growing season.

To gain a more mechanistic understanding of tillage effects on loblolly pine productivity, more intensive physiological measurements were taken during the second growing season. Photosynthesis and leaf water potential measurements were taken four times from May 1998 through October 1998. (May 19-22, July 7-10, August 18-21, September 29-30 and October 1-2). One block of treatments was measured per day during each of the 4-day periods.

Photosynthesis was measured using a Li-Cor 6400 photosynthesis system (Li-Cor, Inc., Lincoln, Nebraska). Two trees were measured in the morning. Measurements were repeated on one of these trees in the afternoon. Up to three fascicles per tree were placed in the measurement chamber. Each tree had approximately five measurements taken.

Leaf water potential was measured using a pressure bomb. Two fascicles from two trees were measured from each of the 16 plots. Pre-dawn and mid-day measurements were taken. The trees used for measuring water potential were the same trees used for photosynthesis.

Soil water content was assessed at the same time from loose soil samples collected at 10-cm increments to a depth of 50 cm (where possible). Two samples were obtained near each tree and composited. Gravimetric moisture content was determined on the composite samples by oven drying at 105^0C for 24 hours, and converted to volumetric moisture content using the bulk density data.

Belowground Tree Sampling

The trench-profile method (Böhm, 1979) was used to assess tillage effects on pine root exploitation of the soil profile. The root sampling was done in November 1998 following the second growing season. Two representative trees were selected from the treated buffer area in each plot. A backhoe pit was dug beginning 0.3 m from the tree and centered on the planting row. The pit was approximately 0.8-m wide by 0.9-m deep, and extended 1.4-m perpendicular to the planting row. One face of the pit was carefully smoothed off and a 1.2-m length by 0.8-m height sampling frame was place on the face. The sampling frame was segmented into 10- by 10-cm sections. Roots within 0.1 cm of the face were exposed and counted in each 100-cm^2 section. Root counts are expressed as roots per 100 cm^2.

Statistical Analysis

Soil tillage effects on aboveground tree measurements were examined using analysis of variance for a factorial experiment in a randomized complete block design using a two-factor, fixed effects model.

Soil tillage effects on soil properties and root exploitation were examined with analysis of variance for a split-split plot design using a four-factor, fixed effects model, with perpendicular distance from the planting row and soil depth as the split-plot factors.

The analysis of variance was done on plot means obtained from averaging the within plot subsamples. Effects were considered significant if $p>F$ was ≤ 0.10.

RESULTS

Pre-tillage Soil Physical Properties

Bulk density ranged from 1.44 g cm^{-3} in the surface 10-cm to 1.60 g cm^{-3} in the 10 to 20-cm depth (Table 1). Soil texture was sandy loam in the surface 20-cm, grading to clay at the 40- to 50-cm depth. The increase in bulk density in the 10- to 20-cm depth indicates the presence of a relic plow pan still evident from past agricultural use. The lower bulk density in the surface 10 cm is attributed to the influence of root penetration and organic matter incorporation that has occurred since agricultural abandonment. Aeration porosity drops from 15 % in the surface 10-cm to 3 % at the 40- to 50-cm depth. This rapid drop in aeration porosity follows a shift in the pore size distribution to smaller diameter pores with increasing clay content at depth.

Table 1. Pre-tillage soil physical characteristics.

			Volumetric Soil Water Content				
Depth	Bulk Density	Soil Texture	Field at Tillage	Saturation	Field Capacity†	Wilting Point‡	Aeration Porosity¶
- cm -	- g cm^{-3} -		- - - - - - - - - - - -	- - - % - - -	- - - - - - - - - - - -		
0 – 10	1.44	SL	20	44	23	9	15
10 – 20	1.60	SL	19	40	27	14	9
20 – 30	1.55	SCL	23	41	32	24	6
30 – 40	1.48	CL	27	44	37	27	5
40 – 50	1.44	C	28	45	41	32	3

† water held at –0.03 MPa
‡ water held at –1.5 MPa
¶ percent of total soil volume in pores greater than 60 µm

Tillage Effects on Soil Physical Properties

Tillage had significant effects on bulk density with depth and distance from the planting row (Table 2). All treatments reduced the bulk density at 0 cm from the planting row (Table 3). Subsoiling had the greatest effect on bulk density in the planting row, reducing bulk density by 0.18 g cm^{-3} versus 0.08 g cm^{-3} for disking alone. There was a negative interaction between disking and subsoiling in the two-pass treatment, which produced intermediate effects. The subsoiling effect on bulk density was less pronounced at 30 cm, with no effects evident at 60 cm from the planting row. Disking reduced bulk density of the surface 20 cm of soil, while subsoiling reduced bulk density at all depths (Table 4). In effect, subsoiling made bulk density more uniform with depth.

Table 2. Analysis of variance results for the effects of surface (disk) and subsurface (subsoil) tillage, location (3 located at 30-cm intervals perpendicular to planting row), and depth (5 depths at 10-cm increments), and their interactions on soil physical properties one year following tillage.

Effect	Bulk Density	Total Porosity	Rooting Volume†	Aeration Porosity	Field Capacity	Wilting Point	Available Water‡
	- - - - - - - -	- - - - - - - -	- - - - - - - -	p > F	- - - - - - - -	- - - - - - - -	- - - - - - - -
Disk	0.501	0.592	0.883	0.675	0.155	0.197	0.944
Subsoil	0.048	0.083	0.001	0.001	0.215	0.441	0.176
Location	0.000	0.000	0.000	0.000	0.650	0.096	0.044
Depth	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Disk x Subsoil	0.272	0.190	0.401	0.032	0.501	0.995	0.924
Disk x Location	0.617	0.878	0.441	0.808	0.660	0.236	0.748
Disk x Depth	0.086	0.607	0.741	0.764	0.011	0.513	0.359
Subsoil x Location	0.000	0.009	0.027	0.049	0.158	0.166	0.963
Subsoil x Depth	0.064	0.089	0.324	0.819	0.078	0.904	0.149
Location x Depth	0.729	0.378	0.720	0.202	0.945	0.324	0.516
Disk x Subsoil x Location	0.019	0.217	0.559	0.729	0.195	0.993	0.122
Disk x Subsoil x Depth	0.697	0.267	0.126	0.396	0.272	0.234	0.455
Disk x Location x Depth	0.544	0.776	0.226	0.237	0.341	0.798	0.308
Subsoil x Location x Depth	0.618	0.512	0.557	0.734	0.511	0.886	0.387
Disk x Subsoil x Location x Depth	0.780	0.319	0.307	0.093	0.902	0.290	0.791

† percent of total soil volume in pores greater than 140 µm
‡ field capacity minus wilting point

Subsoiling was the only treatment that affected total porosity (Table 2). Total porosity increased in the planting row with subsoiling by 0.05 $cm^3\ cm^{-3}$ (Table 5). Subsoiling increased total porosity at all depths except the 10- to 20-cm depth (Table 6).

Of all the physical properties tested, aeration porosity was the most sensitive to the tillage treatments, as indicated by the high level of significance and the number of multiple interactions (Table 2). Disking increased aeration porosity by about 0.025 $cm^3\ cm^{-3}$ in

Table 3. Tillage effects on bulk density with distance from the planting row.

	Bulk Density (g cm^{-3}) Distance from planting row (cm)		
Treatment	0	30	60
None	1.50 a†	1.52 a	1.50
Disk	1.42 b	1.47 ab	1.47
Subsoil	1.32 c A‡	1.43 bc B	1.48 B
Subsoil + Disk	1.35 c A	1.41 c B	1.47 C

† Values within columns (locations) followed by different lower case letters are significantly different at alpha = 0.10.
‡ Values within rows (treatments) followed by different upper case letters are significantly different at alpha = 0.10.

Table 4. Tillage effects on bulk density with depth.

	Bulk Density by Treatment			
Depth	None	Disk	Subsoil	Subsoil + Disk
cm	- - - - - - - - - - - - -	g cm^{-3}	- - - - - - - - - - - - -	
0 – 10	1.44 a† A‡	1.38 b A	1.37 b A	1.37 b A
10 – 20	1.60 a B	1.48 b B	1.53 b B	1.51 b B
20 – 30	1.55 a B	1.53 a C	1.41 b A	1.42 b A
30 – 40	1.48 a AB	1.46 a B	1.39 b A	1.38 b A
40 – 50	1.44 a A	1.43 a B	1.35 b A	1.38 b A

† Values within rows (depths) followed by different lower case letters are significantly different at alpha = 0.10.
‡ Values within columns (treatments) followed by different upper case letters are significantly different at alpha = 0.10.

Table 5. Subsoiling effects on total porosity with distance from the planting row.

	Total Porosity (cm^3 cm^{-3}) Distance from planting row (cm)		
Treatment	0	30	60
None	0.45 a†	0.43 a	0.43 a
Subsoil	0.50 b A‡	0.45 a B	0.44 a B

† Values within columns (locations) followed by different lower case letters are significantly different at alpha = 0.10.
‡ Values within rows (treatments) followed by different upper case letters are significantly different at alpha = 0.10.

Table 6. Subsoiling effects on total porosity with depth.

Depth	Total Porosity by Treatment	
	None	Subsoil
cm	- - - - - cm^3 cm^{-3} - - - - -	
0 – 10	0.46 a† A‡	0.49 b A
10 – 20	0.42 a B	0.41 a B
20 – 30	0.42 a B	0.46 b A
30 – 40	0.44 a AB	0.48 b A
40 – 50	0.46 a A	0.49 b A

† Values within rows (depths) followed by different letters are significantly different at alpha = 0.10.
‡ Values within columns (treatments) followed by different upper case letters are significantly different at alpha = 0.10.

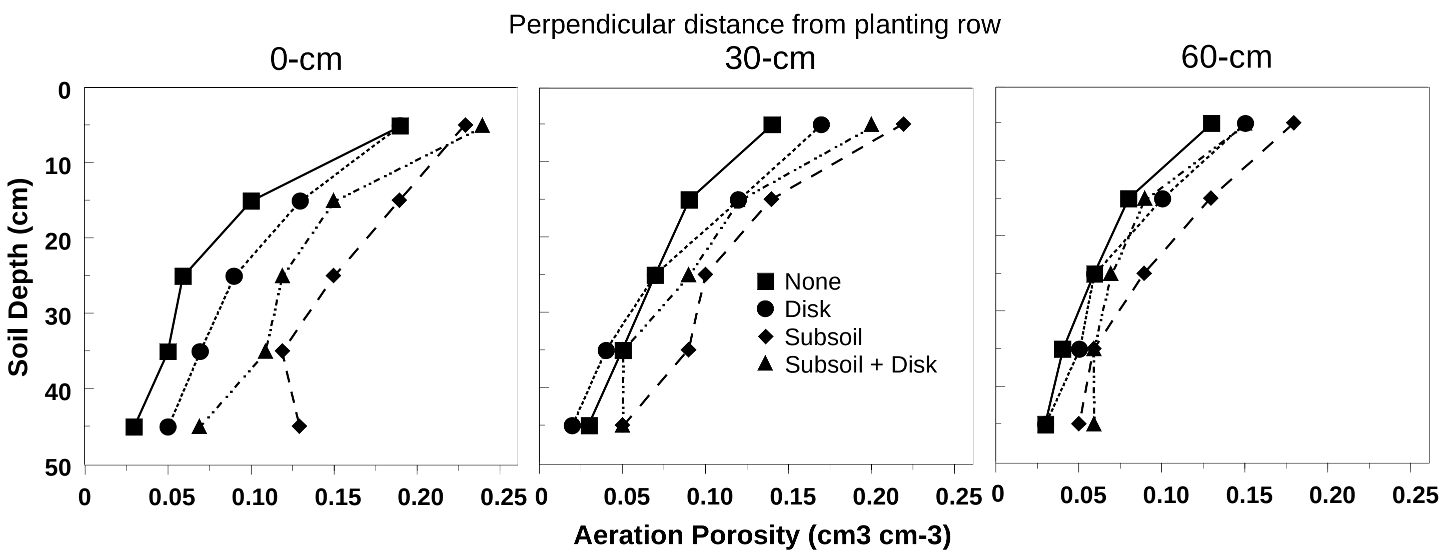

Figure 1. Soil tillage effects on aeration porosity with depth and distance from the planting row.

the surface 20 cm of soil at 30 and 60 cm from the planting row (Fig. 1). Subsoiling increased aeration porosity by 25% in the surface 10 cm in the planting row. The magnitude of the subsoiling effect increased with depth, with subsoiling at least doubling aeration porosity at all depths below 10 cm. Subsoiling increased aeration in the surface 20-cm depth at 30 cm from the planting row, and in the surface 10-cm depth at 60 cm from the planting row. There was a negative interaction between disking and subsoiling in the two-pass treatment, with this treatment producing intermediate effects.

Disking increased field capacity at the 10- to 20-cm depth, while subsoiling decreased field capacity in the surface 30 cm of soil (Table 7). Subsoiling + disking produced intermediate effects.

Table 7. Tillage effects on field capacity with depth.

	Field Capacity by Treatment			
Depth	None	Disk	Subsoil	Subsoil + Disk
cm	- - - - - - - - - - - - - $cm^3\ cm^{-3}$ - - - - - - - - - - - - -			
0 – 10	0.23 a† A‡	0.24 a A	0.21 b A	0.21 b A
10 – 20	0.27 a B	0.30 b B	0.23 c A	0.28 ab B
20 – 30	0.32 a B	0.32 a B	0.29 b B	0.33 a B
30 – 40	0.37 BC	0.37 BC	0.36 C	0.38 C
40 – 50	0.41 C	0.41 C	0.41 C	0.39 C

† Values within rows (depths) followed by different lower case letters are significantly different at alpha = 0.10.
‡ Values within columns (treatments) followed by different upper case letters are significantly different at alpha = 0.10.

Table 8. Subsoiling effects on rooting volume with distance from the planting row.

	Rooting Volume ($cm^3\ cm^{-3}$) Distance from planting row (cm)		
Treatment	0	30	60
None	0.05 a†	0.05 a	0.04 a
Subsoil	0.12 b A‡	0.08 b B	0.07 a B

† Values within columns (locations) followed by different lower case letters are significantly different at alpha = 0.10.
‡ Values within rows (treatments) followed by different upper case letters are significantly different at alpha = 0.10.

Subsoiling had a large impact on rooting volume, increasing rooting volume from 0.05 to 0.12 $cm^3\ cm^{-3}$ in the planting row (Table 8). This effect diminished at 30 cm and was not evident at 60 cm from the planting row. On a whole soil basis, subsoiling increased rooting volume by 0.03 $cm^3\ cm^{-3}$ when accounting for the percent soil volume affected.

Table 9. Analysis of variance results for the effects of surface (disk) and subsurface (subsoil) tillage, location (12 located at 10-cm intervals perpendicular to planting row), and depth (8 depths at 10-cm increments), and their interactions on root exploitation of the soil profile two years following tillage.

Effect	Root Count
	$p > F$
Disk	0.383
Subsoil	0.589
Location	0.000
Depth	0.000
Disk x Subsoil	0.422
Disk x Location	0.653
Disk x Depth	0.836
Subsoil x Location	0.338
Subsoil x Depth	0.069
Location x Depth	0.000
Disk x Subsoil x Location	0.006
Disk x Subsoil x Depth	0.213
Disk x Location x Depth	0.978
Subsoil x Location x Depth	0.240
Disk x Subsoil x Location x Depth	0.009

Tillage Effects on Root Exploitation

The tillage treatments had significant effects on root exploitation of the soil profile (Table 9). The number of roots decreased with depth and distance from the planting row (Fig. 2). Roots extended to 60- to 70-cm deep for the non-tilled soil after two years. Roots had only extended from 40- to 50-cm deep for the disk treatment during this period.

Fewer roots were observed in the surface 0- to 10-cm depth in the planting row with subsoiling, but subsoiling resulted in a more uniform distribution of roots with depth at this location. Subsoiling was the only treatment where roots were observed at the maximum sampling depth of 70 to 80 cm. Disking had more roots in the surface 0 to 20 cm of soil at 60 cm from the planting row when compared to subsoiling. The subsoiling + disking treatment resulted in root distributions intermediate between disking and subsoiling.

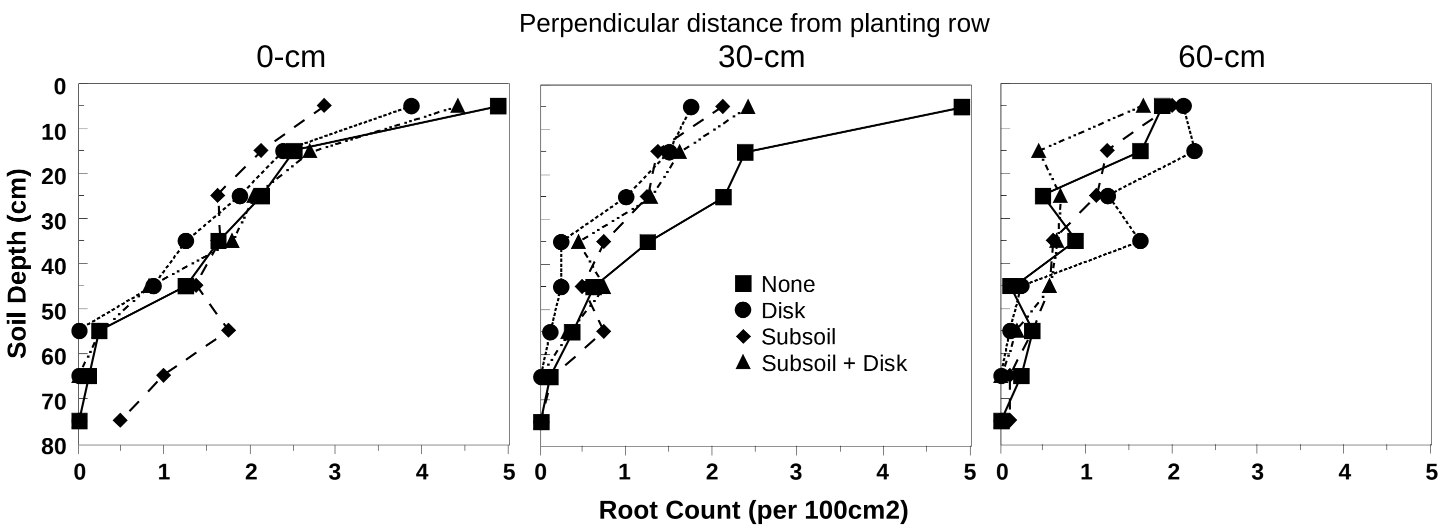

Figure 2. Tillage effects on root exploitation of the soil profile of two-year-old loblolly pine.

Table 10. Tillage effects on total number of root tips and rooting volume.

Treatment	Root Count	Rooting Volume Index†
	roots / 100-cm^2	%
None	0.97	61
Subsoil	0.82	59
Disk	0.79	54
Subsoil + Disk	0.82	58

† Number of cells with roots present divided by the total number of cells.

Tillage Effects on Aboveground Tree Growth and Physiological Processes

The tillage treatments had no effects on total height or groundline diameter after two growing seasons (Table 11). The average height and groundline diameter were 79 and 2.45 cm, respectively. The predawn water potentials were –0.60 MPa or better during the second growing season (Table 12), indicating little or no plant water stress on any of the treatments at anytime. Light saturated photosynthesis rates were uniformly high across all treatments on the newly developing foliage in May and dropped to 3 to 5 μmol/m^2/sec in August and September (Table 13).

Table 11. Aboveground growth of two-year-old loblolly pine by tillage treatment.

Treatment	Total Height	Groundline Diameter
	- - cm - -	- - cm - -
None	78	2.4
Subsoil	77	2.3
Disk	72	2.3
Subsoil + Disk	90	2.8

Table 12. Predawn loblolly pine water potentials (MPa) during the second growing season by tillage treatment.

Treatment	Predawn water potential (MPa)			
	May	July	August	September
None	-0.61	-0.62	-0.50	-0.51
Subsoil	-0.68	-0.65	-0.59	-0.55
Disk	-0.65	-0.47	-0.55	-0.56
Subsoil + Disk	-0.62	-0.65	-0.54	-0.65

The physiological response data are corroborated by the volumetric soil water content results. The tillage treatments had no effects on volumetric soil water content. The volumetric soil water content was similar for each sampling time, with the lowest observation being 0.13 cm^3 cm^{-3} for the surface 0 to 10 cm in May, 1998 (Table 14). The volumetric soil water content was just below field capacity (Table 1) for all depths at all sampling times during the summer of 1998.

Table 13. Light saturated photosynthesis rates (µmol / m^2 / sec) during the second growing season (May, July, August, September 1998) by tillage treatment.

Treatment	Light saturated photosynthesis rates (µmol / m^2 / sec)		
	May	August	September
None	8.1	3.1	5.4
Subsoil	8.9	3.6	5.1
Disk	8.8	4.1	3.9
Subsoil + Disk	9.4	3.3	5.3

Table 14. Volumetric soil water content with depth during the second growing season (May, July, August, September 1998).

	Volumetric Soil Water Content (cm^3 cm^{-3}) by Month			
Depth (cm)	May	July	August	September
0 – 10	0.13	0.18	0.18	0.18
10 – 20	0.28	0.25	0.25	0.25
20 – 30	0.34	0.31	0.31	0.31
30 – 40	0.40	0.34	0.34	0.36
40 – 50	0.36	0.36	0.36	0.39

DISCUSSION

Tillage Effects on Soil Physical Properties

The critical bulk density's that have been reported for reduced root growth are 1.65, 1.60, 1.45, and 1.40 g cm^{-3} for sandy loam, sandy clay loam, clay loam, and clay textured soils, respectively (Daddow and Warrington, 1983; Morris and Campbell, 1991). The bulk density of the surface 10 cm is well below the critical level, but the bulk density's for the remaining depths are at or near their respective critical levels (Table 1). A widely reported critical level for soil aeration is 10% air-filled porosity (Foil and Ralston, 1967; Childs et al., 1989; Theodorou et al., 1991). Oxygen diffusion becomes severely restricted at aeration porosity's less than 10%, making aerobic respiration difficult. The surface 10 cm is well aerated, but aeration porosity falls below the critical level at the 10- to 20-cm depth, reaching a low of 3% at 40- to 50-cm depth. The near-critical bulk density's and low aeration porosity's suggest that this soil would be an excellent candidate for ameliorative tillage for improving the soil physical environment and increasing tree growth.

Though the tillage treatments affected multiple soil physical properties, aeration porosity and bulk density were the most sensitive indicators of tillage effects on the soil. Large increases in aeration porosity and reductions in bulk density were observed with subsoiling down to the 50-cm plowing depth in the planting row. The volume of soil affected by subsoiling will depend on if the subsoiler is operated at the critical depth. The critical depth is the maximum depth of subsoiling, and occurs where the shearing resistance for upward soil flow equals the resistance for lateral flow (Spoor and Godwin, 1978). When a subsoiler is operated at the critical depth, a 45 degree rupture plane will form beginning on the outer edge of the wing tip. Our subsoiler had a wing tip extending 15 cm from the shank; thus, when operated at 50-cm depth the soil should have fractured on the 45 degree plane out to 65 cm from the shank, if the subsoiler was set at the critical depth. Based on this criteria, the subsoiler was set near the critical depth, since increased aeration porosity was still evident in the surface 10 cm of soil at 60 cm from the planting row.

The subsoiling treatment was installed on a 2.7-m spacing. Assuming that all subsoiling was done at the critical depth, then approximately 24 % of the upper 50 cm of soil volume per hectare was affected by subsoiling. On a whole soil basis this would equate to a 0.01 cm^3 cm^{-3} increase in aeration porosity over the non-tilled soil. Since roots typically only occupy about 1 to 2% of the soil volume (Wolkowski, 1990), this increase may be biologically significant. However, given the small amount of total soil volume affected by subsoiling, the period of tree growth response to tillage may be short.

Disking had minimal effects on soil physical properties compared to subsoiling. The lack of a disking effect on aeration porosity in the planting row suggests that the disks did not penetrate 100% of the soil surface in the treatment plots; logging slash and stumps probably caused the disks to jump out of the soil at several locations.

The tillage effects on soil physical properties indicate that subsoiling is a superior treatment compared with disking or the two-pass subsoil + disk treatment. The longevity of the subsoiling effect on soil physical properties is unknown. Because of multiple annual trafficking, agricultural soils are subsoiled every four years (Parker and Amos, 1982; Soane et al., 1987). Since the trafficking frequency is much lower on forest soils, the subsoiling effect should persist for a longer period of time than in agriculture.

Tillage Effect on Below- and Aboveground Growth

Root distributions were significantly altered by the tillage treatments. Subsoiling resulted in more roots at depth in the vicinity of the planting row. Deeper rooting is considered the primary benefit attributed to subsoiling, as deeper rooting means potentially greater plant access to available water and nutrients located deeper in the soil profile (Unger, 1979; Chancy and Kamprath, 1982). Root growth was restricted to the surface 40 to 50 cm with disking. Surface tillage practices have been shown to decrease root penetration deeper in the soil profile (Ehlers et al., 1983; Goss et al., 1984). Surface tillage disrupts macropore continuity (Wolkowski, 1990). The net effect is a more tortuous pathway for root growth when compared to undisturbed forest soils, which would limit the growth of roots, and also water movement, into the subsoil.

Rooting patterns coincide roughly with the changes in aeration porosity produced with tillage. We know that gas diffusion decreases exponentially as air-filled porosity decreases, becoming severely limited for oxygen supply at 10% air-filled porosity. However, the critical volumetric soil water content where gas diffusion becomes critical for root growth actually varies depending on soil texture, structure, and organic matter content (Freijer, 1994), and aggregate size and shape (Renault and Stengel, 1994). In addition, residual root channels and cracks from shrink / swell (abundant slicken-sides were noted in the subsoil) would be major pathways for gas diffusion, and may balance out any reduced aeration measured in the bulk soil matrix. The soil is also well-drained, and seldom experiences long periods of saturation, thus low aeration porosity may not be important. So, the weak relationship between rooting patterns and aeration porosity probably doesn't reflect improved aeration for root growth, but rather higher aeration porosity is most likely indicating a less tortuous physical pathway for root growth.

The rooting volume index was not a sensitive measurement of tillage effects on soil physical properties, nor did the index relate in any discernable way to rooting patterns. The lack of a discernable relationship between the rooting volume index and rooting patterns probably reflects that soils are semi-rigid systems, meaning that roots can penetrate smaller pores by enlarging them, as well as preferentially grow through old root channels and cracks.

While the tillage treatments did have significant effects on the distributions of two-year-old pine roots, the total number of pine roots counted did not differ among treatments (Table 10). The average number of pine roots was 0.85 roots per 100 cm^2 of soil. If we can equate total number of pine roots to the amount of absorbing surface, then there was no treatment difference in the potential amount of water and nutrients roots could intercept and take up. The percent of sample cells where roots were observed was used as an index of the amount of soil volume exploited by roots (Table 10). As with the total number of pine roots, there were no treatment effects, with an average of 58% of the cells having roots present. For all tillage treatments 75% of the roots were observed growing within 70 cm of the planting row. Roots were observed extending past our maximum sampling distance of 120 cm after the first two years of growth. At this expansion rate, it is expected that root systems of adjacent planting rows will close within 3 years after planting.

Why didn't we see a tillage effect on aboveground growth given that initial soil physical conditions appeared to be limiting? Tillage influences growth through a combination of beneficial effects on competition control, nutrient availability, water availability, and reducing rooting restrictions (Unger, 1979; Wolkowski, 1990). We reduced the effects of competition, and nutrient and water availability by chemical vegetation control and fertilization, but based on the initial soil physical conditions we hypothesized that excess soil strength (indicated by high bulk density) and / or poor soil aeration may limit growth on this site. The vast amount of research done in agriculture has demonstrated that subsoiling increases growth when it alleviates moisture stress, having no effect on growth when there is adequate available water (Unger, 1979; Marks and Soane, 1987; Soane et al., 1987; Wolkowski, 1990). The predawn water potential and volumetric soil water content results showed that available water was not a limiting factor on this site, thus there was no moisture stress limitation present for tillage to overcome.

What about physical restrictions preventing root growth? Physical restrictions to root growth can occur for one of three reasons: 1) high soil strength; 2) poor soil aeration; and 3) inadequate available water. Available water and poor soil aeration have all ready been discounted as growth limiting factors on this site for the 1998 growing season.

As was stated earlier, the pre-tillage bulk density's were at levels reported to reduce root growth. The critical bulk density's often reported in the literature (e.g. Morris and Campbell, 1991) are an oversimplified surrogate for soil strength. Studies have shown that root growth is severely restricted above 2.0 MPa soil strength (da Silva and Kay, 1997). Soil strength is a function of bulk density, clay content, organic matter content, and volumetric soil water content. Thus for a given soil, strength may or may not be growth limiting depending on the volumetric soil water content. Published regression equations (da Silva and Kay, 1997) were used to predict soil strength monthly at each depth for the 1998 growing season (Table 15). The highest soil strength predicted was 1.14 MPa, which is considerably lower than the published critical level. Thus, the pre-tillage soil physical conditions did not restrict root growth during the 1998 growing season.

Table 15. Predicted soil strength† with depth during the second growing season (May, July, August, September 1998).

	Soil Strength (MPa) by Month			
Depth (cm)	May	July	August	September
0 – 10	1.14	1.08	1.08	1.08
10 – 20	0.93	1.10	1.10	1.10
20 – 30	0.73	1.01	1.01	1.01
30 – 40	0.34	0.72	0.72	0.55
40 – 50	0.58	0.58	0.58	0.35

† Soil strength was predicted using equations published by da Silva and Kay, 1997.

We did not collect any data during the 1997 growing season, so the soil environmental and tree physiological conditions for the first year are not known. Monthly precipitation data from the nearby weather station are shown to elucidate first year effects (Fig. 3). Less precipitation was recorded during the first five months of 1997 compared to the same time period in 1998. However, with the exception of May, 1997, the monthly data was similar to the 40-yr average monthly rainfall. Thus, it appears that the trees were exposed to similar environmental conditions during their first growing season.

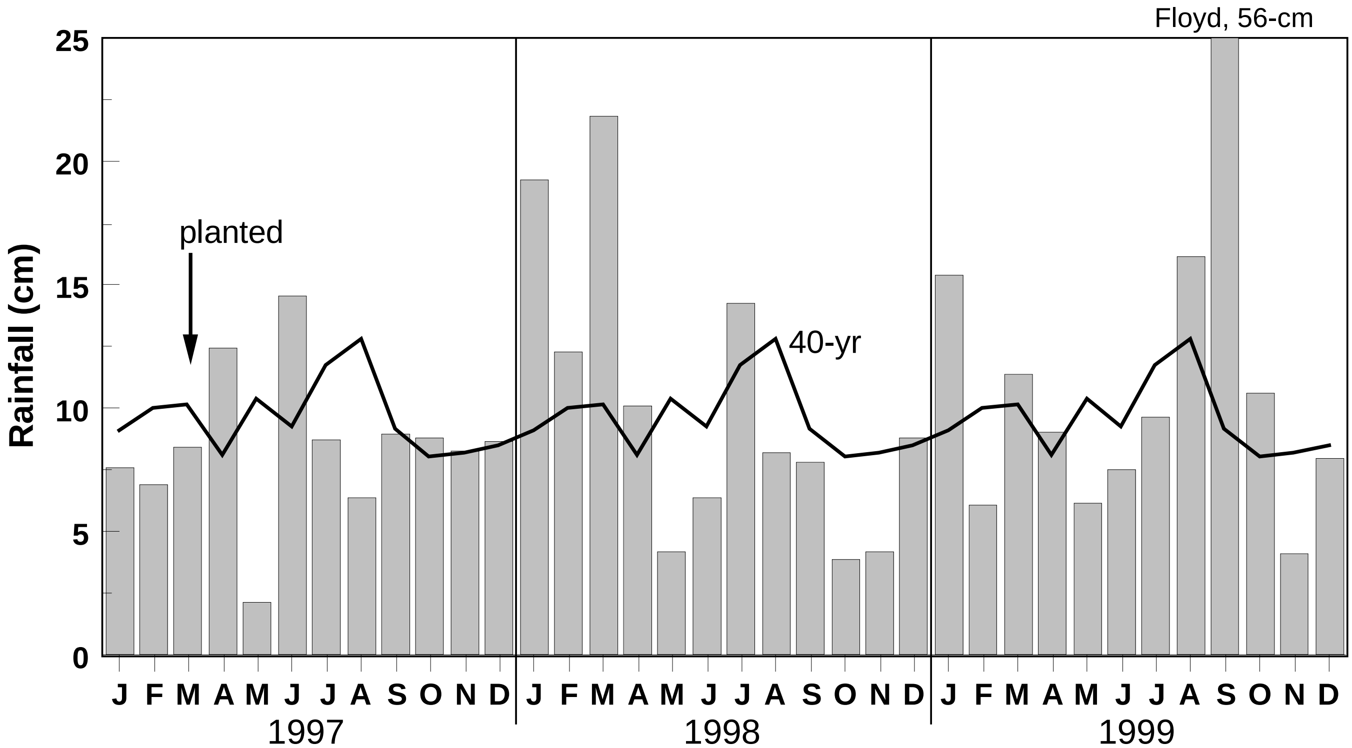

Figure 3. Monthly rainfall measured at a NOAA cooperative weather station located approximately 6-km from the study site in Arcola, N.C. Vertical bars are monthly precipitation recorded during the study period. The black line represents the historical 40-yr average monthly precipitation.

Consistent with the agricultural experience, trials conducted on droughty soils have documented significant early tree growth responses to subsoiling. A subsoiling by vegetation control factorial trial located on a well-drained, rocky, fine-textured soil in southeastern Oklahoma showed that subsoiling improved 2-yr-old loblolly pine tree height by 10%, vegetation control by 23%, and the combination by 49% compared to an untreated control (Wittwer et al., 1986). The subsoiling effect is difficult to fully interpret given that subsoiling would have simultaneously increased nutrient availability, provided some competition control, and improved soil physical properties. But, given the droughty location, and high density of the soil, it is likely that subsoiling did improve root growth and access to available water by ameliorating soil physical limitations.

In plantations growing on a poorly-drained, fine-textured soil in South Africa, total height and ground line diameter of 2-yr-old Radiata pine (*Pinus radiata* D. Don.) were 11% higher with subsoiling + standard vegetation control compared to standard vegetation control only (South et al., 1993). However, subsoiling + total vegetation control had no effect on tree growth compared to total vegetation control alone, even though subsoiling most likely did improve soil physical properties (aeration in this case). South and others concluded that competing vegetation limited growth more than soil physical properties on this site. Removing competing vegetation should result in lasting positive effects on tree growth as available water and nutrients are continuously allocated to the crop trees. On the other hand, subsoiling effects are probably short-term since natural ameliorative processes such as shrink / swell will likely return the soil to its pre-tillage physical condition in a few years. Also, roots in non-tilled soils will grow into old root channels and through voids created during shrink / swell and eventually occupy the same soil volume as roots in tilled soils.

On two well-drained eroded Piedmont sites, subsoiling + vegetation control doubled 1-yr-old loblolly pine stem volume on one site and quadrupled stem volume on the other compared with vegetation control only (Morris et al., 1988). In this study, subsoiling was accomplished with two shanks mounted in tandem on the tool bar, so the volume of soil affected would have been much greater than in our study. In the absence of a fertilization treatment it is difficult to evaluate the subsoiling effect. It is likely, however, that with the greater volume of soil disturbance from two shanks, both nutrient mineralization and vegetation control would have been enhanced beyond the levels normally experienced with single shank subsoiling.

Our results are consistent with other studies conducted on shrink/swell clay soils, where subsoiling had no effect on 1- (Haines, 1978) and 2-yr-old (NCSFNC, 1998) pine growth on soils that had received vegetation control and fertilization prior to tillage. The lack of a response on shrink / swell soils illustrates the fact that roots don't grow in the bulk soil matrix, but rather they grow in the void spaces created by cracking and old root channels.

CONCLUSIONS AND RECOMMENDATIONS

Subsoiling was more effective at reducing bulk density and increasing aeration porosity than disking or the two-pass subsoiling + disking treatment. Subsoiling was the only tillage treatment that resulted in any potential beneficial changes in root distributions, with subsoiling resulting in more roots at depth in the planting row. The greater number of roots at depth with subsoiling may be advantageous for increasing plant access to available water and nutrients located deeper in the soil profile, and would probably provide benefits to early tree growth if available water and/or nutrients were limiting.

The 1998 tree physiological and soil moisture measurements showed that available water did not limit tree growth at any time during the growing season on this site. In addition, a modelling analysis showed that soil strength was not a limiting factor for root growth, even though tillage did alter rooting patterns. Based on the apparent abundance of available water and lack of soil strength problems, there were no soil physical limitations on this site for tillage to overcome. Thus, tillage had no effects on 2-yr-old loblolly pine tree growth when competing vegetation was controlled and nutrient deficiency's were minimized.

It is important to understand that if vegetation control and / or fertilization were not going to be employed the results of other studies show that tillage can improve early tree growth. In our situation, the pre-tillage soil physical conditions suggested a soil wherein tree growth would be responsive to tillage. But, the results of our study point to the need for us to develop better diagnostics for identifying sites were tillage is appropriate in situations where fertilization and vegetation control are also planned. Our traditional measures of soil physical properties seem to be inadequate for characterizing the state of the environment for root growth. The importance of the bulk soil matrix is probably overemphasized. Additional factors to consider are presence and abundance of old root channels, soil shrink / swell capacity, soil structure, presence and depth to root restricting layers, and historical precipitation records.

When candidate sites are identified, the next step is to choose the appropriate tillage method. Results from field trials vary depending on the configuration of tillage equipment (e.g. single versus double-shank subsoiling). To more fully evaluate the efficacy of tillage, more research is needed on designing and evaluating tillage methods appropriate for forestry. Based on the tillage methods we employed subsoiling was the best treatment given it's superior performance in improving soil physical properties.

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