Impacts of harvesting and postharvest treatments on soil bulk density, soil strength, and early growth of *Pinus taeda* in the Gulf Coastal Plain: a Long-Term Soil Productivity affiliated study[1]

Mason C. Carter, Thomas J. Dean, Ziyin Wang, and Ray A. Newbold

Abstract: At four sites in the Gulf Coastal Plain, mechanical whole-tree harvesting (MWT) removed more biomass and nutrients than hand-fell bole-only harvesting (HFBO). Soil compaction and loblolly pine (*Pinus taeda* L.) regeneration growth varied among sites. At one location, MWT increased soil bulk density by 0.1 Mg·m^{-3}, from 1.14 to 1.24 Mg·m^{-3}, with no effect on tree growth. At a second location, where bulk density increased by 0.1 Mg·m^{-3}, from 1.41 to 1.51 Mg·m^{-3}, pine growth was reduced significantly. Soil strength at 15–20 cm depth increased by 0.3–0.5 MPa at both locations. However, where MWT reduced pine growth, herbaceous weed control mitigated the effect. Fertilization with N and P, where P was limiting, increased pine growth irrespective of other treatments. Where P was not limiting, addition of a complete fertilizer reduced the mitigating effect of weed control. Bedding reduced soil compaction without improving early tree growth; however, bedding was not tested on the two sites where soil compaction appeared to be at critical levels. Broadcast burning increased survival but reduced pine growth irrespective of harvesting method. Our results suggest that the impact of intensive management on site productivity varies among sites, is potentially accumulative, and is subject to change over time.

Résumé : Dans quatre stations de la plaine côtière du golfe du Mexique, la récolte mécanisée par arbres entiers (MAE) a enlevé plus de biomasse et de nutriments que la récolte manuelle du fût seulement (MFS). La compaction du sol et la croissance de la régénération de pin à encens (*Pinus taeda* L.) varient selon la station. À un endroit, la récolte MAE a entraîné une augmentation de la densité apparente de 0,1 Mg·m^{-3} qui est passée de 1,14 à 1,24 Mg·m^{-3} sans qu'il y ait d'effet sur la croissance des arbres. À un autre endroit où la densité apparente a augmenté de 0,1 Mg·m^{-3}, passant de 1,41 à 1,51 Mg·m^{-3}, la croissance du pin a été réduite de façon significative. La résistance du sol à une profondeur de 15–20 cm a augmenté de 0,3 à 0,5 MPa aux deux endroits. Cependant, là où la récolte MAE a réduit la croissance du pin, la maîtrise de la végétation herbacée en a atténué l'effet. La fertilisation avec N et P, où P est un facteur limitant, a augmenté la croissance du pin peu importe les autres traitements. Aux endroits où P n'est pas un facteur limitant, l'addition d'un fertilisant complet a réduit l'effet d'atténuation de la maîtrise de la végétation. Le billonnage a réduit la compaction du sol sans améliorer la croissance juvénile des arbres. Cependant, le billonnage n'a pas été testé dans les deux stations où la compaction du sol a semblé atteindre un niveau critique. Le brûlage extensif a augmenté le taux de survie mais réduit la croissance du pin peu importe la méthode de récolte. Les résultats indiquent que l'impact de l'aménagement intensif sur la productivité d'une station varie selon la station, est potentiellement cumulatif et sujet à changement dans le temps.

[Traduit par la Rédaction]

Introduction

Some of the practices commonly used in southern pine plantation management have the potential to reduce soil productivity. Soil compaction by heavy forest machines and consequent adverse impacts on early pine growth are well documented (Froehlich 1979; Greacen and Sands 1980; Hatchell 1981; Wert and Thomas 1981; Lockaby and Vidrine 1984; Corns 1988; Aust et al. 1998; Brais and Camire). Several authors have cautioned that the removal or displacement of nutrient-rich biomass during whole-tree harvesting and site preparation may impoverish the soil (Kimmins 1977;

Received 14 March 2005. Accepted 22 October 2005. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 9 March 2006.

M.C. Carter,[2,3] **T.J. Dean, and Z. Wang.**[4] School of Renewable Natural Resources, Louisiana State University Agricultural Center, Baton Rouge, LA 70803, USA.
R.A. Newbold. School of Forestry, Louisiana Tech University, Ruston, LA 71272, USA.

[1]This article is one of a selection of papers published in the Special Issue on Long-Term Soil Productivity.
[2]Corresponding author (e-mail: masoncarter@comcast.net).
[3]Present address: 1907 Canopy Court, Fort Collins, CO 80528, USA.
[4]Present address: Texas Parks and Wildlife, 4200 Smith School Road, Austin, TX 78744, USA.

 doi:10.1139/X05-248

Tippin 1978; Leaf 1979). However, the amount of biomass removed and the degree of soil disturbance vary considerably during harvesting and regeneration operations, and commercial forest owners frequently employ cultural practices such as soil tillage and fertilization designed to mitigate adverse effects and (or) enhance productivity (Allen et al. 1990; Aust et al. 1998; Fox 2000). Such cultural practices, together with variations in local climatic conditions and the introduction of new genotypes, may obscure adverse changes in the processes that govern soil productivity between rotations (Stanturf et al. 2003).

A number of long-term field studies have been initiated to monitor the impacts of management practices on soil productivity (Tew et al. 1986; Hendrickson et al. 1989; Powers et al. 1990; Johnson and Todd 1998; Briggs et al. 2000). The largest of these studies, the USDA Forest Service Long-Term Soil Productivity (LTSP) study, is designed to assess the impact of three levels of soil compaction (C_0, C_1, C_2) and three levels of organic matter removal (OM_0, OM_1, OM_2) in all combinations applied as uniformly as possible over the treatments plot (Powers et al. 1990). For the minimum impact treatment, OM_0C_0, no machinery is allowed on the plots and no organic matter is removed except the boles of merchantable trees (Powers et al. 1990). The LTSP study should provide response surfaces that relate the effects of a given level of soil compaction and (or) organic matter removal on tree growth, but the treatments do not simulate operational practices, and most of the installations do not include mitigating treatments. Other studies (Tew et al. 1986; Hendrickson et al. 1989; Johnson and Todd 1998; Briggs et al. 2000) compared several intensities of industrial practices but did not include a minimum impact treatment comparable to the LTSP OM_0C_0 treatment.

In 1994 a cooperative research program involving forest industries, universities, and the USDA Forest Service was formed (Powers et al. 1996; Powers 2006) with the following objectives:

(1) Determine the influence of site characteristics on response to plantation management.
(2) Derive knowledge of soil properties and processes affecting productivity and impacts of management on these processes.
(3) Complement and interpret the findings from LTSP for loblolly pine (*Pinus taeda* L.) plantation management.

Studies were initiated at four sites along the Gulf Coastal Plain during 1994–1995. All installations included a minimum impact harvesting treatment comparable to the OM_0C_0 treatment in the LTSP study, along with conventional harvesting and two or more postharvest cultural treatments. This report presents the effects of harvesting and postharvest treatments on soil compaction, organic matter removal, and growth of the regenerated stand at age 5 years.

Methods and materials

Study sites

All sites are located in ecoregion provinces 231 or 232, which are part of the subtropical division of the humid–temperate domain (Bailey 1997, 1998), in the Gulf Coastal Plain of the United States. Prior to harvesting, each site was occupied by a well-stocked, planted or direct-seeded stand of loblolly pine. Table 1 contains soils and stand data prior to harvesting. A general description of each site follows.

Fragipan site

This site is located in St. Helena Parish, Louisiana, on property owned by International Paper Company. Elevation ranges from 28 to 32 m above sea level, with slopes <3%. Precipitation averages 168 cm·year^{-1}. The soil is Toula series, a very deep, moderately well drained soil with a fragipan occurring between 45 and 65 cm. Permeability is moderate in the upper part of the subsoil and slow in the fragipan. These soils formed in a moderately thick deposit of loess over loamy Coastal Plain sediments. The taxonomic classification is fine-silty, siliceous, thermic Typic Fragiudult. The site was probably cultivated and abandoned sometime prior to the 20th century. The existing 19-year-old plantation of loblolly pine was established following clear-cutting of a naturally regenerated pine–hardwood mixed forest. Site preparation methods, if any, are not known. The stand had not been thinned or burned.

Lowland site

The site is located in Tyler County, Texas, on property owned by Temple Inland Forest Products Corporation. Elevation is 40–42 m above mean sea level, and average precipitation is 136 cm·year^{-1}. The soil is Kirbyville series, a very deep, moderately well drained, moderately permeable soil formed in loamy Coastal Plain sediments of mid-Pleistocene age. The taxonomic class is fine-loamy, siliceous, semiactive, thermic Oxyaquic Paleudults. Slopes are 0% to 3%. The site has no history of post-Columbian cultivation. At time of harvest, the site was occupied by a 27-year-old stand of loblolly pine, established by direct seeding following harvesting of a natural stand of mixed pine. Site preparation prior to direct seeding consisted of broadcast burning and disking. The stand was thinned in corridors spaced at ~10 m intervals at age 15 years. At least one surface fire had occurred since crown closure.

Old-field site

This site is located on a broad terrace of the Flint River in Decatur County, Georgia, on property owned by International Paper Company. Elevation is ~ 27 m, and precipitation averages 167 cm·year^{-1}. The soil series is Hornsville, fine, kaolinitic, thermic Aquic Hapludult. This is a very deep, moderately well drained soil formed in loamy and clayey sediments. Slopes are <3%. The site has a long history of agricultural use but had been in fallow for several years prior to establishment of the existing stand, a 30-year-old progeny trial of loblolly pine. The planting was mowed frequently until crown closure and then burned at 3- to 5-year intervals.

Upland site

This site is located in Bienville Parish, Louisiana, on property owned by Willamette Industries, Inc. Mean elevation is 94 m, and precipitation averages 137 cm·year^{-1}. The soil series is Mahan, a deep, well drained, moderately permeable soil formed in loamy and clayey sediments. The taxonomic classification is fine, kaolinitic, thermic Typic Hapludult. The site lies in hilly uplands in the Western Coastal Plains province. Slope ranges from 5% to 10%. Agricultural history

Table 1. Preharvest stand characteristics and surface soil descriptions for the experimental sites.

	Study site			
Attribute	Fragipan	Lowland	Old-field	Upland
Age at harvest (years)	19	27	30	31
SI at age 25 (m)	19	18	23	18
Pine BA ($m^2 \cdot ha^{-1}$)	25.7	28.0	28.5	22.2
Hardwood BA ($m^2 \cdot ha^{-1}$)	4.3	2.5	0	3.7
Years since last fire	>19	>5	3	>5
No. of thinnings	0	1	2	2
Pine foliage nutrient conc. ($mg \cdot g^{-1}$)				
N	11.9	12.8	11.9	14.8
P	0.88	0.79	1.06	1.10
K	3.54	3.68	4.52	4.28
Ca	2.13	2.19	2.32	2.07
Soil series	Toula	Kirbyville	Hornsville	Mahan
Soil subgroup	Typic Fragiudults	Oxyaquic Paleudults	Aquic Hapludults	Typic Hapludults
Surface texture (0–30 cm)	0–30 cm: silt loam	0–30 cm: fine sandy loam	0–22 cm: fine sandy loam, 22–30 cm: sandy clay	0–12 cm: fine sand loam, 12–30 cm: sandy clay
Soil pH	4.7	4.9	5.1	5.0
Soil nutrients (0–10 cm, $kg \cdot ha^{-1}$)*				
N	791	429	543	773
P	1.4	2.6	8.7	3.7
K	21	32	20	47
Ca	124	269	358	304

Note: Locations of the sites are as follows: fragipan, St. Helena Parish, Louisiana; lowland, Tyler County, Texas; old-field, Decatur County, Georgia; upland, Bienville Parish, Louisiana. BA, basal area; SI, site index.

*Total N; P extracted with 0.03 mol/L NH_4F in 0.1 mol/L HCL; cations extracted with 1.0 mol/L NH_4OAc (pH 7).

of this site is unknown but there is no indication of severe erosion that would be expected if the site had a long history of cultivation. The existing 31-year-old stand had been planted following the harvest of a mixed pine forest. The plantation had been thinned twice and subjected to several surface fires.

Preharvest biomass and soil measurements

Before harvesting, experimental blocks, based on soil structure and slope position, were established within an area of 12–15 ha. Each block was divided into six or eight treatment plots, with buffer zone ≥20 m on at least two sides of each plot. The height and DBH (1.3 m) of all trees ≥5 cm DBH were measured before harvesting in all plots except at the old-field site. Biomass by components was estimated using regression equations from Baldwin (1987) for pine and Clark et al. (1985) for hardwoods. Three dominant or co-dominant pines were felled on each plot to provide samples and to reconstruct the growth of the stand using stem analysis. Starting at ground line, a disc was removed every 0.5 m for 10 m and then every 1 m from 10 m to the tip. From the 0, 5, and 10 m discs, a 22.5° wedge was removed. Wood and bark were separated and composited by plots. Samples of pine needles and branches were collected from the upper, middle, and lower thirds of the crown of each felled tree and composited. Nutrient content for overstory hardwoods was estimated based on Messina et al. (1986) and Phillips et al. (1989).

To estimate understory biomass, each main plot was divided into four quadrants, and a 2 m × 4 m subplot was located at random in each quadrant. All live vegetation <5 cm DBH was clipped weighed, and subsampled for moisture determination and chemical analyses. Samples of the forest floor to mineral soil were collected from four randomly located 0.1 m × 0.1 m subplots, weighed, and subsampled for later analyses.

The stand at the old-field site, a progeny trial, was measured annually for the first 15 years and at 3-year intervals thereafter. Biomass for the pine stand was calculated using equations from Taras and Clark (1974). Foliage, branch, and bole samples of pine were collected from trees randomly selected during the harvesting operation. Sampling methods for the understory and litter were the same as those at the other sites.

All plant samples were dried at 70 °C to a constant mass and ground to pass a 20-mesh stainless steel screen. Nitrogen concentration was determined with a Fisons Instruments Model EA 1108 CHN analyzer (Quorum Technologies, Newhaven, East Sussex, UK). For other elements, samples were wet ashed in nitric acid – hydrogen peroxide (Huang and Schulte 1985) and analyzed with an inductively coupled plasma emission spectrophotometer.

Soil samples for chemical analysis were collected prior to harvesting with a push tube (2.0 cm i.d.) from five random locations in each plot and composited, returned to the laboratory, air dried, and sieved to pass a 2 mm screen. To determine available P, 2.5 g of soil was placed in 50 mL of 0.03 mol/L NH_4F in 0.1 mol/L HCL, shaken 15 min, filtered, and analyzed colorimetrically (Olsen and Sommers 1982). For exchangeable cations, 2.5 g of soil was placed in 25 mL of 1.0 mol/L NH_4OAc (pH 7), shaken 15 min, filtered, and analyzed in inductively coupled plasma emission spectrophotometer. Total soil C and N were determined using a Fisons Instruments CHN analyzer.

Experimental design and treatments

Two harvesting systems used at all sites were

(1) Hand-fell bole-only harvesting (HFBO) — Merchantable trees (DBH ≥15 cm) were felled, limbed, and topped with handheld chain saws. Tree boles were lifted from the plots by a crane or grapple loader positioned outside the plot area. No mechanical equipment traversed the plots during harvesting. This is the equivalent of the LTSP study's minimum impact treatment, OM_0C_0.
(2) Mechanical whole-tree harvesting (MWT) — Merchantable trees were felled, bunched, and skidded to the loading deck where they were topped and limbed. Four-wheel feller–bunchers with a typical mass of 10–11 Mg were used at the lowland, old-field, and upland sites. Three-wheel machines with a typical mass of 6–7 Mg were used at the fragipan site.

Soil moisture at all sites was well below field capacity during harvesting.

Site preparation and other cultural treatments were based on current operational prescriptions for each site. Herbicide was applied by air before planting to all treatments. A combination of imazapyr and glyphosate was used at the fragipan, old-field, and upland sites. Imazapyr and trichlopyr were applied at the lowland site. It is unlikely that aerial spraying influenced soil compaction or biomass removal.

Postharvest cultural treatments at the fragipan site were (1) aerial spray (AS), (2) AS and herbaceous weed control (HWC) consisting of imazapyr and sulfometuron applied on a 1.1 m band), (3) AS and a single pass with a bedding plow (Bed). Treatments at the lowland site were (1) AS, (2) AS and 250 $kg \cdot ha^{-1}$ diammonium phosphate applied after planting (DAP), (3) AS and a single pass with bedding plow equipped with a subsoiling device (Rip–Bed), (4) AS, DAP, and Rip–Bed. Treatments at the old-field site were (1) AS, (2) AS and HWC (two applications of sulfometuron and imazapyr in 2% aqueous solution of glyphosate as directed spray), (3) AS, HWC, and complete fertilizer at rate of 56 $kg\ N \cdot ha^{-1}$ applied in a circular band around each tree (CF). Treatments at the upland site were (1) AS, (2) AS and HWC (hexazinone and sulfometuron applied on a 1.1 m band), (3) AS and broadcast burning after harvesting (Burn).

Sites were hand planted with bare-root 1–0 loblolly pine seedlings grown from seed orchard stock. The first planting at the lowland site suffered heavy mortality from pales weevil (*Hylobius pales* Marsh.). Surviving seedlings were pulled up in August 1995, a second aerial spray was applied, and the area was replanted. Plots at the upland, fragipan, and lowland sites consisted of 14 rows of 14 trees at a 2 m × 3 m spacing. Plots in the old-field site consisted of 11 rows of 40 trees at a 2.44 m × 2.44 m spacing. The experimental design was a randomized block with a factorial combination of harvesting and postharvest treatments.

Postharvest measurements

Two years after harvesting at the upland and fragipan sites and 3 years after harvesting at the lowland and old-field sites, soil bulk density (BD) was determined at 30 cm inter-

Table 2. Aboveground biomass and nutrient content for the four experimental sites prior to harvesting.

			Nutrient content (kg·ha⁻¹)				
Site	Component	Biomass (Mg·ha⁻¹)	N	P	K	Ca	Mg
Fragipan	Pine boles	66.4	71.5	4.4	39.2	101.9	23.9
	Pine tops	24	161.2	9.5	53	59	19.7
	Other standing biomass	22.5	81.2	4.2	36.4	113.3	15.9
	Forest floor	32.8	332.6	11.2	23.6	223.8	37.7
	Total	145.7	646.5	29.3	152.2	498	97.2
Lowland	Pine boles	94.1	72.1	6.1	58.5	134.9	34.8
	Pine tops	18.3	121.2	7.6	39.2	38.5	15.7
	Other standing biomass	21.2	108.1	5.3	51.8	136.9	29.5
	Forest floor	19.8	123.3	4.5	9.5	100.7	19
	Total	153.4	424.7	23.5	159	411	99
Old-field	Pine boles	210.1	142.8	12.2	90.9	249.4	73.4
	Pine tops	28.2	115.9	10.7	51	52.3	19.9
	Other standing biomass	2.5	21.7	2.5	17.2	19	24.5
	Forest floor	22.6	199.2	12.7	20.7	101.1	19.2
	Total	263.4	479.6	38.1	179.8	421.8	117.1
Upland	Pine boles	103.5	83.7	4	49.1	145.4	29.1
	Pine tops	11.4	108.9	7.4	33	20.1	8.9
	Other standing biomass	17.3	43.3	4.9	27.6	50.8	8.6
	Forest floor	10.5	75.8	4	8.7	58.2	8.9
	Total	142.7	311.7	20.3	118.4	274.5	55.5

vals to a depth of 150 cm. Soil cores were collected at four locations in each plot with a Veihmeyer soil sampling tube (1.9 cm i.d.) and composited. Subsamples were removed for chemical analyses, and the remainder of the sample was dried at 105 °C to a constant mass. Results are presented for 0–30 and 30–60 cm soil depths only, since none of the treatments affected soil BD below 60 cm.

Three years postharvest at the fragipan and upland sites and 4 years postharvest at the lowland and old-field sites, soil strength was measured from 0–60 cm with a Rimik cone penetrometer (Agridry, Queensland, Australia) at 1.5 cm intervals during vertical insertion of the 30° angle cone probe. Measurements were made at 12 locations per plot, three per row at 5 m intervals in each of the four middle rows. Since soil strength is highly influenced by soil moisture content (Morris and Campbell 1991), all measurements were made when soil moisture was at or just slightly below field capacity. Soil moisture at 30 cm depth was measured with a Quick Draw soil moisture probe (Soilmoisture Equipment Corp., Santa Barbara, California) at random points to insure that moisture did not vary significantly among plots.

At the lowland, fragipan, and upland sites, survival and total height were recorded annually for 100 trees (the middle 10 rows of 10 trees), and ground-line diameter or DBH was recorded for 20 trees (middle 4 rows of 5 trees) for all plots. At the old-field site, diameter and height for 252 trees (7 rows of 36 trees) were recorded annually beginning at age 2 years. Additional tree measurements were recorded on subplots but are not included in this report. Unfortunately, a wildfire burned across the fragipan site near the end of the fourth growing season, killing all planted pine in two of the three blocks.

The effectiveness of weed control was assessed at the end of the first growing season (late August and early September) at the fragipan and upland sites. Three 1.0 m × 0.25 m rectangular subplots were established in every main plot. Each subplot was within a tree row with one short side touching a planted tree. All living herbaceous vegetation inside the subplot was clipped, bagged, dried at 65 °C to a constant mass, ground, and subsampled for elemental analyses as previously described.

Statistical analysis

Analysis of variance was used to test the main effects and interactions on plot means for herbaceous vegetation and tree growth and on plot means at each depth for soil strength and BD. All analyses and individual treatment comparisons by the Bonferroni test were carried out using SYSTAT version 9 (SPSS Inc., Chicago, Illinois). Unless stated otherwise, all references to significant differences are based on $\alpha = 0.05$.

Results and discussion

Biomass and nutrient removals

Table 2 shows the mass and nutrient content of the aboveground biomass prior to harvesting, and Table 3 compares the biomass and nutrients removed by the two harvesting treatments. At all sites, mechanical whole-tree harvesting (MWT) removed more biomass and nutrients than hand-fell bole-only harvesting (HFBO), but relative differences decreased with increasing stand age (Tables 1 and 3). In loblolly pine stands, the accumulations of biomass and N content of crown and stem bark culminate at about age 23 years, while the biomass in bole wood continues to increase (Smith et al. 1963). Thus, the amount of N removed per tonne of pine boles during MWT decreases with increasing age beyond ~23 years (Switzer et al. 1981). In the current

Table 3. Biomass and nutrients removed by hand felling and removing merchantable tree boles only (HFBO) compared with mechanical whole-tree harvesting (MWT).

			Nutrients removed (kg·ha^{-1})				
Site	Harvest treatment	Biomass removed (Mg·ha^{-1})	N	P	K	Ca	Mg
Fragipan	HFBO	65.1	63.1	4.1	39.6	105.7	22.7
	MWT	100.2	243.5	14.5	102.1	202.3	46.8
	Ratio*	1.5	3.9	3.5	2.6	1.9	2.1
Lowland	HFBO	77.5	58.5	5.0	48.2	111.2	28.7
	MWT	112.4	193.3	13.7	97.7	173.4	50.5
	Ratio*	1.5	3.3	2.7	2.0	1.6	1.8
Old-field	HFBO	210.7	143.9	12.2	91.7	248.9	73.8
	MWT	237.1	259.0	22.9	142.0	303.7	93.7
	Ratio*	1.1	1.4	1.9	1.6	1.2	1.3
Upland	HFBO	104.2	84.2	4.1	48.5	145.5	28.9
	MWT	115.6	193.3	11.4	81.7	164.7	37.7
	Ratio*	1.1	2.3	2.8	1.7	1.1	1.3

*MWT/HFBO.

study, MWT removed 2.4, 1.7, and 1.6 kg N·Mg^{-1} of pine boles from 19-year-old fragipan, 27-year-old lowland, and 31-year-old upland stands, respectively, and 1.1 kg N·Mg^{-1} of pine boles from the highly productive, 30-year-old stand at the old-field site.

Tew et al. (1986) reported that complete-tree harvesting removed 2.0 kg N·Mg^{-1} of pine boles in a 22-year-old loblolly pine plantation in North Carolina, United States.

In the North Carolina study, whole-tree harvesting removed 1.7, 3.2, 4.0, 2.5, 3.5, and 2.5 time as much biomass, N, P, K, Ca, and Mg, respectively, as stem-only harvesting (Tew et al. 1986). At the fragipan and lowland sites — stands of similar age to the one in North Carolina — we found the ratio of removals by MWT versus HFBO to be lower except for N and K (Table 3). Hardwoods, which represented 30% of the basal area in the North Carolina stand, were included in removals by whole-tree but not in the stem-only harvesting (Tew et al. 1986). None of the stands in our study exceeded 15% hardwood (Table 1), and hardwoods were not removed by either harvesting system except at the fragipan site where merchantable hardwoods were removed in both the whole-tree and bole-only harvests. The different treatment of hardwoods probably accounts for the higher removal of biomass, P, Ca, and Mg reported by Tew et al. (1986).

Soil compaction

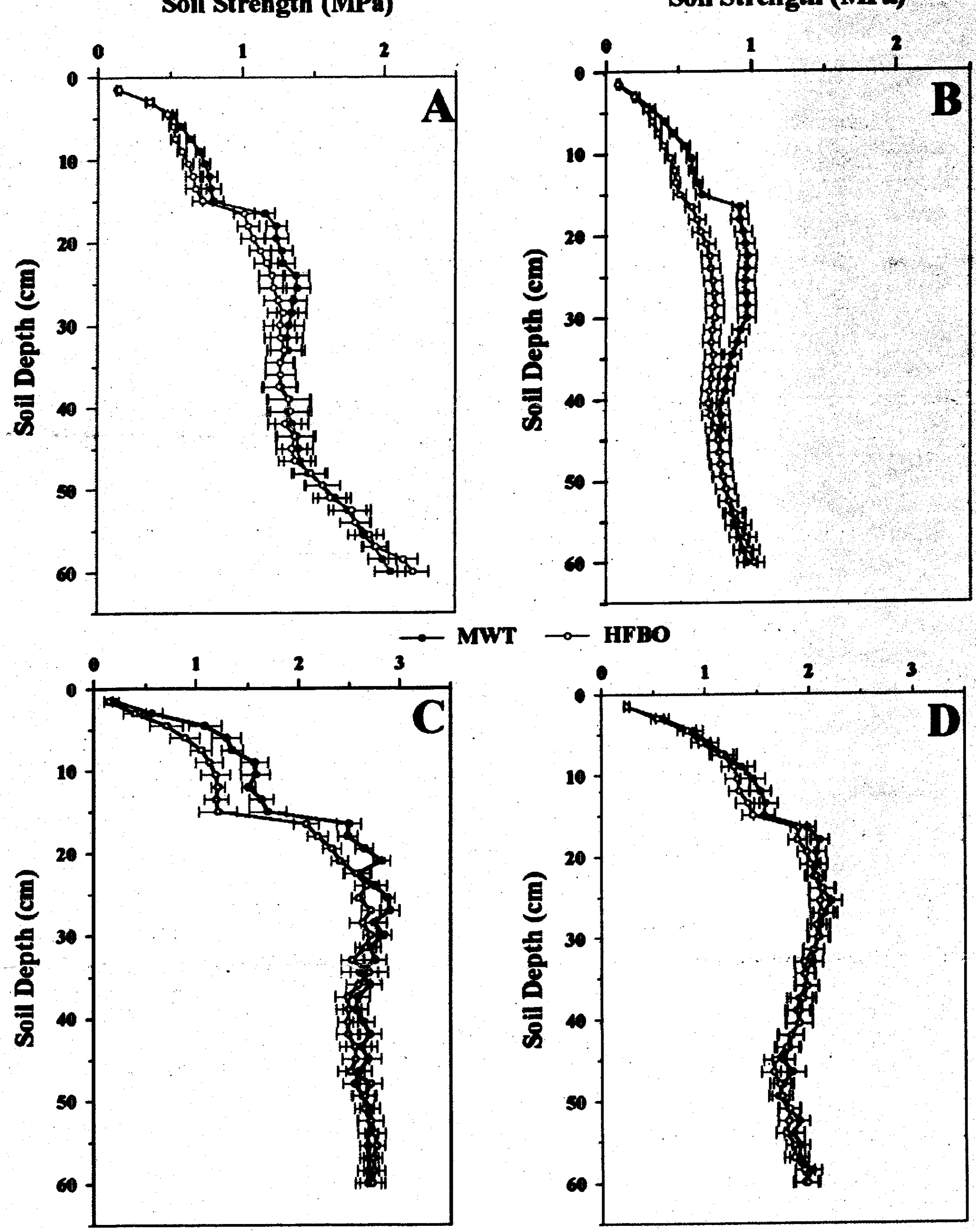
MWT increased the BD of the surface 30 cm of soil at the lowland and old-field sites (Table 4). Soil strength was significantly increased at all sampling depths between 6 and 40 cm at the lowland site and at seven points between 6 and 27 cm at the old-field site (Figs. 1B and 1C). At the fragipan site, MWT did not significantly increase soil BD (Table 4) but soil strength was significantly higher at 7.5, 9.0, and 10.5 cm depths (Fig. 1A). These finding are in general agreement with those of Gent et al. (1983, 1984), who found that mechanical harvesting increased soil BD in the 0–7.5 cm depth zone on sandy soils in the North Carolina coastal plain and in the 0–8 and 8–15 cm depth zones of a clayey soil in

Table 4. Effects of harvesting method and postharvest treatments on soil bulk density.

		Soil depth	
Site	Main treatment	0–30 cm	30–60 cm
Fragipan	HFBO	1.10	1.47
	MWT	1.16	1.46
	p	0.1977	0.6786
	AS	1.23a	1.46
	AS + HWC	1.18a	1.48
	AS + Bed	0.99b	1.45
	p	0.0037	0.8508
Lowland	HFBO	1.14	1.42
	MWT	1.24	1.48
	p	0.0030	0.1153
	AS	1.29	1.49
	AS + Rip–Bed	1.10	1.41
	p	0.0001	0.0442
Old-field	HFBO	1.41	1.61
	MWT	1.51	1.60
	p	0.0426	0.7633
	AS	1.43	1.58
	AS + HWC	1.49	1.64
	AS + HWC + CF	1.46	1.60
	p	0.4533	0.1705
Upland	HFBO	1.34	1.50
	MWT	1.36	1.51
	p	0.3580	0.8401
	AS	1.32b	1.53
	AS + HWC	1.41a	1.4
	AS + Burn	1.33b	1.49
	p	0.0094	0.6027

Note: Treatment designations are as follows: HFBO, hand felling with bole-only removal; MWT, mechanical whole-tree harvesting; AS, aerial spray; Bed, single pass with a bedding plow; Rip–Bed, single pass with bedding plow equipped with a subsoiling device; Burn, broadcast burning after harvest; HWC, herbaceous weed control; CF, complete fertilizer. Means within the same study site and soil depth followed by the same letter are not significantly different (α = 0.05).

Fig. 1. The main effects of harvest methods on soil strength profiles at the fragipan (A), lowland (B), old-field (C), and upland (D) sites. HFBO, hand-felling bole-only harvesting; MWT, mechanical whole-tree harvesting. Error bars represent one standard error.



the piedmont. However, the soil strength profiles for lowland (Fig. 1B) and old-field (Fig. 1C) show that the effects of mechanical harvesting extend deeper into the soil than was reported by Gent et al. (1983, 1984), who found no increases in soil compaction below ~20 cm except in main skid trails. In a study in radiata pine (*Pinus radiata* D. Don) in Australia, Lacy and Ryan (2000) found that soil strength, 4 years after harvesting and site preparation, was 0.86 MPa greater at 10–20 cm and 0.64 MPa greater at 20–30 cm depths than it was before treatment, even in areas that appeared to have received little disturbance during the harvesting operations. In rutted areas, soil strength was 1.23 and 1.29 MPa higher at 10–20 and 20–30 cm, respectively. However, all plots were subsoiled prior to replanting, which, the authors concluded, mitigated any adverse effects of soil compaction.

The surface soil texture at the fragipan site is silt loam, while at the other sites it is fine sandy loam (Table 1). Fine-textured soils such as clay loams and silt loams tend to recover from compression more readily than coarser textured sands and sandy loams (Brady 1990). In addition, the harvesting equipment used at the fragipan site was smaller and lighter than that used at other sites. Lighter equipment and soil that is more resilient to compression are the most likely reasons that mechanical harvesting caused less soil compaction at fragipan than at lowland and old-field sites (Table 4, Fig. 1).

At the upland site, we found no significant difference between HFBO and MWT in soil BD (Table 4) or soil strength at any depth (Fig. 1D), although surface soil texture and the equipment used at the upland site were similar to those at the lowland and old field sites. However, at the upland site, soil BD in HFBO plots was 10%–20% higher 1 month after harvesting than it was just prior to harvesting (data not shown). At the other sites, soil BD in HFBO plots after harvesting differed <±5% from preharvest values. Also, soil BD was significantly higher in the AS and HWC plots than in AS or AS and Burn plots (Table 4). These seemingly illogical results suggest that either ambient soil compaction was unusually variable at the upland site or mechanical harvesting equipment inadvertently transgressed one or more of the HFBO plots.

Bedding at the fragipan site and bedding plus ripping at the lowland site significantly reduced soil BD and soil strength (Table 4, Fig. 2). Gent et al. (1983) states that bedding, which removes soil from the furrows and piles it in the center of the bed (Wilhite and Mckee 1986), creates additional rooting space above the compacted zone created by mechanical harvesting but it does not eliminate the compacted zone. The soil strength profiles from the fragipan site (Figs. 2A and 2B) demonstrate Gent's observations. Soil strength (above the fragipan) reached the same maximum in plots that were not bedded (Fig. 2A) and in plots that were bedded (Fig. 2B), but the maximum occurred ~10 cm deeper and was approached more gradually in bedded plots. Gent et al. (1983) cautioned that the remaining compacted zone could have a profound effect on future productivity, since roots could expand laterally along the bed but expansion from side to side or downward through the compacted zone may be restricted. At the lowland site, maximum soil strength in bedded and ripped plots (Fig. 2D) occurred deeper and peaked well below the maximum recorded in plots that were not bedded and ripped (Fig. 2C). Thus, bedding plus ripping more effectively mitigated the soil compaction resulting from mechanical harvesting than bedding alone.

All soil strength profiles in Fig. 1, except for those of HFBO plots at the lowland site (Fig. 1B), show a marked increase in soil strength beginning at ~15 cm, suggesting that compaction from mechanical equipment existed prior to harvesting. The lowland site has no history of post-Columbian cultivation. It was thinned 10–12 years prior to the harvest, but in corridors. The old-field site has a long history of agricultural cultivation. The previous pine stand, a progeny trial, was mowed regularly until crown closure and thinned twice. The upland site was thinned at least twice prior to harvest, but the fragipan site had not been thinned or otherwise traversed by mechanical equipment since the previous harvest 19 years earlier. Both the fragipan and upland sites may have been cultivated previously, but at least two rotations of forest intervened between cultivation and the establishment of the current stands.

Surface soil may recover from compaction by physical processes such as shrinking and swelling in response to moisture changes, shifting and movement associated with freezing and thawing, or biological activities such as root growth and the action of earthworms and soil insects (Brady 1990). However, the soil must be of a type that reacts to the process, and the process must occur at sufficient frequency (Froehlich and McNabb 1984). Soils with 20% or more 2:1 silicate clays expand when wet and shrink when dry to considerable depth (Brady 1990), but the soils in our studies contain 1:1 kaolinitic clays and have less than 20% clay in the surface 15 cm. Freezing and thawing seldom occur deeper than 2–3 cm in the region where our studies are located. In a study of the effects of site preparation on the growth of slash pine (*Pinus elliottii* Engelm.), Tiarks and Heywood (1996) found a zone of high compaction (soil strength of 2 to 3 MPa) between 15 and 30 cm depth in plots that had been disked 33 years earlier. No such compacted zone occurred in plots that had not been disked. In Oregon, Wert and Thomas (1981) reported that soil compaction in the surface 15 cm in skid trails had recovered after 30 years, but below 15 cm depth, soil BD was still 11% to 16% higher than in nondisturbed areas. Thirty-two years after seed-tree removal in an Australian forest, Jakobsen (1983) found that the soil BD was 19% higher in skid trails than in nondisturbed areas for the 2–10 cm depth but 39% higher for the 10–30 cm depth. Our findings add further support to the conclusions of Greacen and Sands (1980) that most soils recover very slowly from compaction below 15 cm and those of Lacey and Ryan (2000) that soil compaction from silvicultural operations may be accumulative.

Herbaceous competition

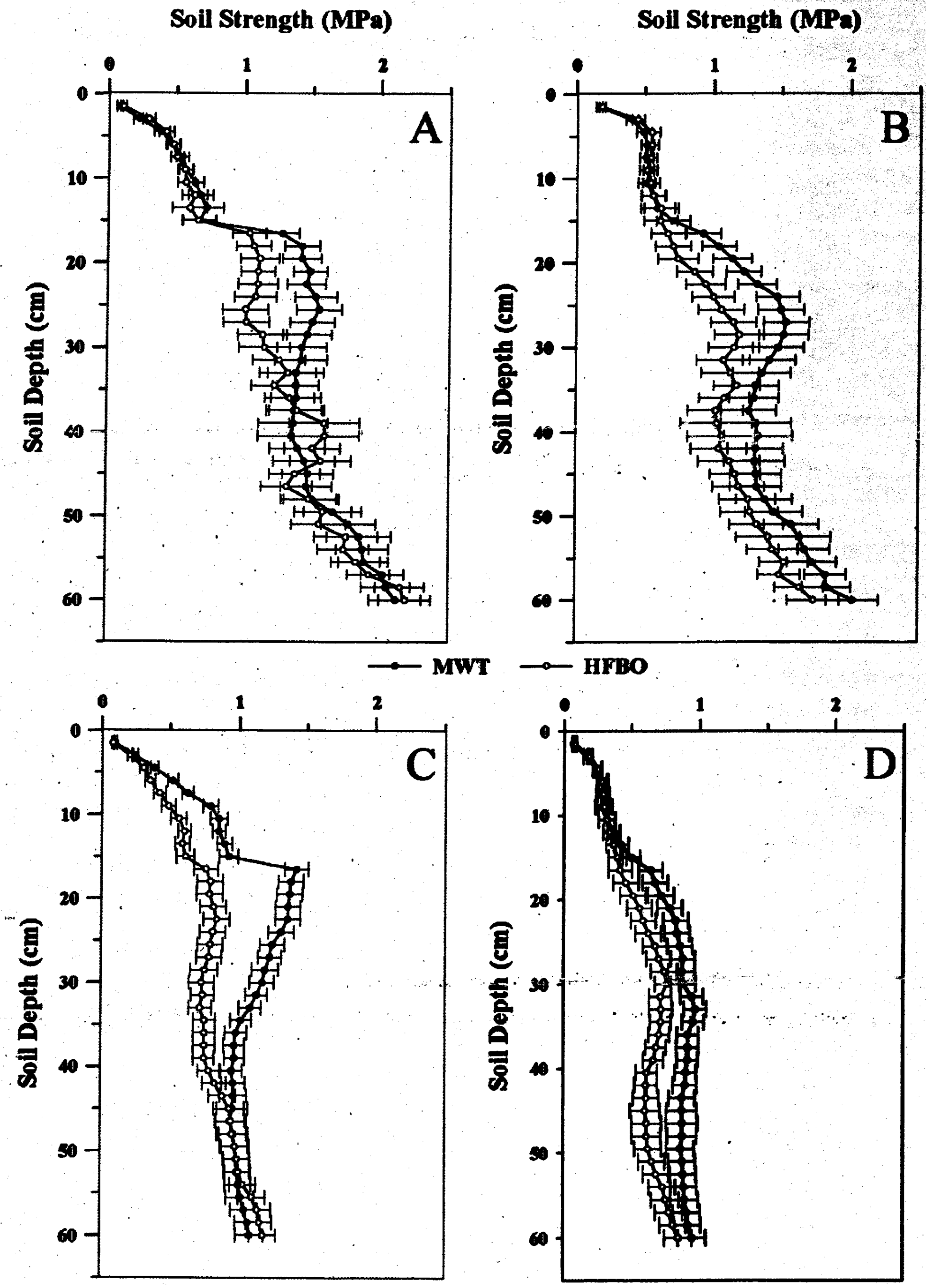
The HWC treatment at the fragipan and upland sites significantly reduced herbaceous biomass, but MWT appeared to stimulate herbaceous growth, at least at the upland site (Table 5). The heavy logging slash on HFBO plots may have acted as mulch and suppressed herbaceous growth, as suggested by Nambiar (1990).

Bedding increases nutrient concentrations and N mineralization in bedded soil (Burger and Pritchett 1984; Fox et al. 1986; Carter et al. 2002), but we observed no significant effect of bedding on biomass or nutrient concentrations in herbaceous vegetation (Table 5).

Harrington et al. (1995) reported that broadcast burning following chemical site preparation increased herbaceous growth, especially grasses, but the main effect of the AS and Burn treatment on herbaceous biomass at the upland site was not significant (Table 5). Neary et al. (1999) concluded that low-impact burning increases plant-available nutrients and promotes herbaceous growth, while high-intensity burning results in nutrient losses and mortality of seed and root systems in the surface soil, thereby leading to reduced herbaceous growth. Jensen et al. (2001) reported that more intense fires reduced total herbaceous biomass but not grasses. HFBO plots at the upland site averaged 11.4 $Mg{\cdot}ha^{-1}$ more pine crown residues than MWT plots, which should have resulted in a more intense fire on the HFBO plots, but this difference in fuel load had little effect on total herbaceous biomass. Unfortunately, we did not separate the herbaceous biomass into grasses and broadleaf components.

Burning increases soil mineral N (Wan et al. 2001), and Grogan et al. (2000) reported higher N concentrations in

Fig. 2. The effect of bedding and ripping plus bedding on soil strength profiles. (A) Fragipan site, not bedded, (B) fragipan site, bedded, (C) lowland site, not ripped and bedded, (D) lowland site, ripped and bedded. Error bars represent one standard error.



herbaceous vegetation growing on recently burned sites. We found no difference in N concentration but significantly lower Ca concentrations in the herbaceous vegetation from burned plots (Table 5).

At the fragipan site, herbaceous vegetation surviving the HWC treatment had increased concentrations of N, P, and Ca. Smethurst and Nambiar (1989) made similar observations in radiata pine plantations in Australia; however, a similar response was not observed at the upland site (Table 5).

Early growth of planted pine seedlings

The main treatment effects on pine survival and growth are shown in Tables 6 and 7. Survival was not affected by

Table 5. The effects of harvesting method and postharvest treatments on the biomass and nutrient concentrations in the herbaceous vegetation at the end of the first growing season following planting.

			Nutrient concentration (mg·g^{-1})				
Site	Main treatment	Biomass (g·m^{-2})*	N	P	K	Ca	S
Fragipan	HFBO	251.5	12.1	0.67	7.83	5.13	2.13
	MWT	332.8	13.7	0.73	9.76	5.76	1.89
	p	0.1230	0.1268	0.4423	0.0541	0.2861	0.7799
	AS	444.3a	10.7b	0.62b	9.11	3.80b	1.57
	AS + HWC	70.9b	17.4a	0.82a	8.49	7.60a	2.18
	AS + Bed	361.3a	10.7b	0.67ab	8.78	4.93b	2.28
	p	0.0002	0.0003	0.0408	0.8616	0.0008	0.4425
Upland	HFBO	242.3	11.5	0.93	14.2	5.95	1.82
	MWT	394.4	11.0	0.80	11.9	4.62	1.72
	p	0.0227	0.6577	0.0889	0.3054	0.0908	0.4597
	AS	401.2a	11.2	0.90	16.1	6.49a	1.93
	AS + HWC	130.7b	13.0	0.79	11.4	5.01ab	1.74
	AS + Burn	448.9a	9.3	0.90	11.2	4.14b	1.62
	p	0.0028	0.1130	0.3278	0.1477	0.0387	0.3450

Note: HFBO, hand felling with bole-only removal; MWT, mechanical whole-tree harvesting; AS, aerial spray; Bed, single pass with a bedding plow; Burn, broadcast burning after harvest; HWC, herbaceous weed control. Means, within locations, followed by the same letter are not significantly different (α = 0.05).

*Data collected within the HWC-treated band.

Table 6. Main effects of harvest method on survival and growth of loblolly pine plantations at age 4 years for the fragipan site and age 5 years for the lowland, old-field, and upland sites.

Site	Harvest method	Height (m)	DBH (cm)	Survival (%)	Volume (m^3·ha^{-1})†
Fragipan*	HFBO	3.04	nd	nd	nd
	MWT	2.85	nd	nd	nd
	p	0.0532	—	—	—
Lowland	HFBO	4.53	6.32	80	12.4
	MWT	4.77	6.68	81	14.8
	p	0.2578	0.5291	0.8546	0.3173
Old-field	HFBO	5.59	9.38	88	33.8
	MWT	5.23	8.73	90	28.7
	p	0.0097	0.0063	0.3015	0.0204
Upland	HFBO	4.77	7.21	88	16.5
	MWT	4.48	6.57	88	13.4
	p	0.1294	0.0462	0.9383	0.1283

Note: HFBO, hand felling with bole-only removal; MWT, mechanical whole-tree harvesting.

*Plantation was heavily damaged by wildfire at the end of the fourth growing season. Survival and DBH were not recorded.

†Stem volume, outside bark, calculated using equation from Baldwin and Feduccia (1987).

any of the treatments except at the upland site where burning increased survival (Table 7). Burning removed most logging debris and improved conditions for hand planting, which may account for the higher survival in burned plots.

MWT confounds biomass removal with soil compaction, so it is not possible to identify the specific cause of any resulting loss in productivity. Previous studies have failed to detect any impact of whole-tree harvesting on growth of the subsequent rotation except on low-productivity sites (Johnson and Todd 1998; Piatek and Allen 1999; Briggs et al. 2000; Smith et al. 2000). The old-field site, where the impact of MWT appeared to be the greatest, is the most fertile and productive of the four sites in the current study (Table 1), suggesting that some factor other than nutrient removal was the cause of reduced pine growth.

MWT increased the BD of the upper 30 cm of soil by 0.1 Mg·m^{-3} at both the lowland and old-field sites (Table 4), but reduced pine growth only at the old-field site (Table 6). Growth-limiting or critical BD is inversely related to silt and clay content and ranges from 1.4 Mg·m^{-3} for fine-textured soils to 1.75 Mg·m^{-3} for coarse-textured soils (Jones 1983; Tuttle et al. 1988). BD in the upper 30 cm at the lowland site was 1.24 Mg·m^{-3} in MWT plots (Table 4), which is well below the critical range of ~1.65 to 1.75 Mg·m^{-3} for a fine sandy loam (Morris and Campbell 1991) such as the Kirbyville pedon (Table 1). However, BD was 1.51 Mg·m^{-3} in MWT

Table 7. Main effects of postharvest treatments on survival and growth of loblolly pine plantations at age 4 years at the fragipan site and age 5 years at the lowland, old-field, and upland sites.

Site	Postharvest treatment	Height (m)	DBH (cm)	Survival (%)	Volume ($m^3 \cdot ha^{-1}$)†
Fragipan*	AS	2.81b	nd	nd	nd
	AS + Bed	2.95ab	nd	nd	nd
	AS + HWC	3.08a	nd	nd	nd
	p	0.0678	—	—	—
Lowland	No Rip–Bed	4.62	6.30	78	12.6
	Rip–Bed	4.69	6.70	83	14.5
	p	0.7205	0.4862	0.1065	0.4138
	No DAP	4.09	5.64	79	8.6
	DAP	5.22	7.36	83	18.6
	p	0.0001	0.0084	0.1095	0.0006
Old-field	AS	4.73 c	7.23b	92	17.7b
	AS + HWC	5.96a	9.91a	89	38.8a
	AS + HWC + CF	5.55b	10.03a	86	37.1a
	p	<0.0001	<0.0001	0.1225	<0.0001
Upland	AS	4.63ab	6.89a	86b	14.8ab
	AS + HWC	4.95a	7.64a	85b	18.3a
	AS + Burn	4.22b	5.99b	94a	11.0b
	p	0.0093	0.0007	0.0291	0.0176

Note: Treatments are as follows: AS, aerial spray; Bed, single pass with a bedding plow; Burn, broadcast burning after harvest; CF, complete fertilizer; DAP, diammonium phosphate; HWC, herbaceous weed control; Rip–Bed, single pass with bedding plow equipped with a subsoiling device. Means, within study sites, followed by the same letter are not significantly different ($\alpha = 0.05$).

*Plantation was heavily damaged by wildfire at the end of the fourth growing season. Survival and DBH were not recorded.

†Stem volume, outside bark, calculated using equation from Baldwin and Feduccia (1987).

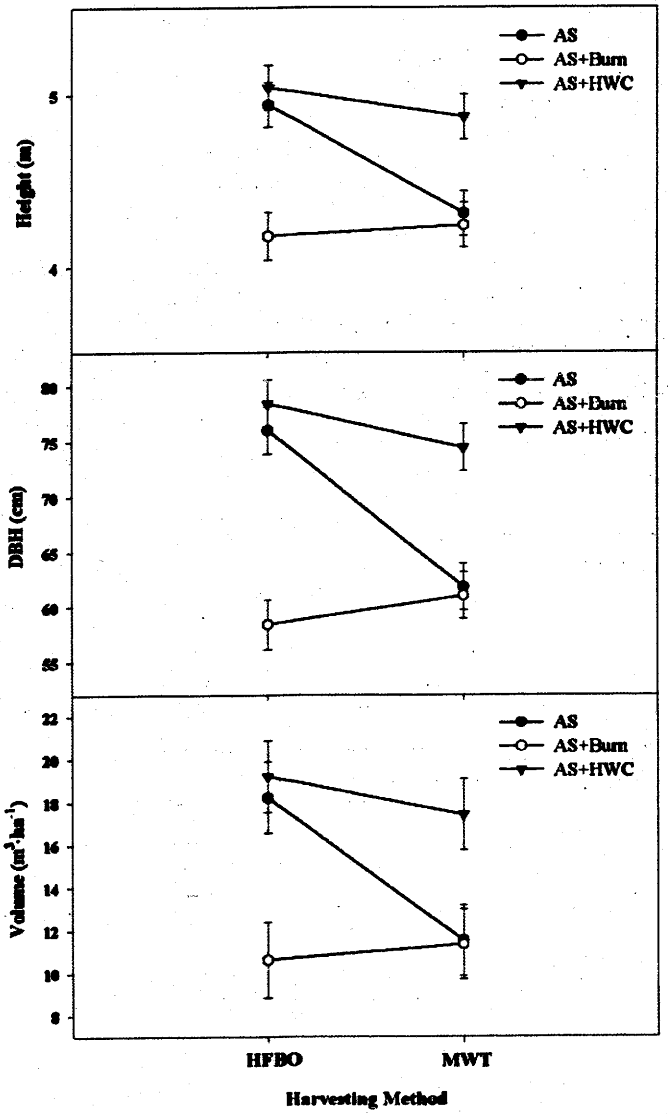
plots at the old-field site (Table 4) and near the critical range of ~1.55 to 1.65 $Mg \cdot m^{-3}$ for sandy clay (Morris and Campbell 1991) such as occurs at ~20 cm in the Hornsville soil (Table 1).

The critical level for soil strength is less dependent upon soil texture than is critical BD (Morris and Campbell 1991). Root growth declines as soil strength increases above 1.0 MPa, and it is severely restricted above 2.0 MPa (Greacen and Sands 1980; Morris and Campbell 1991). Although significantly increased by MWT, soil strength at the lowland site did not exceed ~1.5 MPa in the upper 60 cm (Figs. 1B and 2C). At the old-field site, mean soil strength was 1.0 MPa at 7.5 cm and >2.0 MPa below 16.5 cm in HFBO plots that received only foot traffic during harvesting and site preparation (Fig. 1C). Thus, soil compaction at the lowland site was below a critical level even after MWT, while at the old-field site, it was near or above a critical level prior to harvesting. Ambient values of soil strength and BD were near or above critical levels at the upland site as well, but there were no significant differences between HFBO and MWT (Table 4, Fig. 1D), and the main effect of harvesting method on the pine growth was not significant (Table 6).

However, the reduced pine growth we observed with MWT at the old-field and fragipan sites may not have been caused by soil compaction. At the fragipan site, BD was not increased by MWT (Table 4), and soil strength, though significantly higher at a few points, did not exceed ~1.5 MPa above the fragipan (Fig. 1A). Bedding, which reduced both BD and soil strength (Table 4, Figs. 2A and 2B), had no effect on tree height (Table 7). However, weed control mitigated the effects of MWT at the fragipan and old-field sites, suggesting that increased herbaceous competition rather than increased soil compaction was the cause of decreased pine growth on MWT plots. Further evidence comes from the old-field site, where the HWC and CF treatment was less effective in promoting seedling height growth than HWC alone (Table 7). Mckee and Wilhite (1988) reported that fertilization, especially with N, stimulated herbaceous competition more than newly planted pine seedlings. Lauer and Glover (1997) concluded that when P is not limiting, competing vegetation may respond more to fertilization than planted pine seedlings, and that response to herbaceous weed control is reduced where P is limiting. Critical levels for P in loblolly pine are 1.0 $mg \cdot g^{-1}$ in foliage and 5–6 $mg \cdot kg^{-1}$ in the surface soil (Jokela et al. 1991). At the old-field site, P was above critical levels in both the soil and foliage (Table 1), and the addition of fertilizer reduced the effectiveness of the HWC (Table 7). However, at the fragipan site, both soil and foliage P concentrations were below critical levels (Table 1), and the response to HWC was less than that it was at the old-field and upland sites (Table 7) and was not detected until the third growing season (data not shown).

Broadcast burning at the upland site increased survival but significantly reduced pine height, DBH, and volume at age 5 (Table 7). Minogue and Lauer (1992) reported no differences in pine growth between burn and no-burn treatments following application of 2.2 $kg \cdot ha^{-1}$ active ingredient imazapyr. Harrington et al. (1998) found that burning after application of imazapyr alone increased pine growth but burning after application of imazapyr mixed with glyphosate, triclopyr, or picloram reduced pine growth. They concluded that fire following application of the mixture altered the quality and quantity of the competing vegetation. Our results from the upland site agree with Harrington et al. (1998) in that burning following the application of a mixture of imazapyr and glyphosate reduced pine growth on sites that received HFBO

Fig. 3. Individual treatment means for total height, DBH, and volume at age 5 years for planted pine seedlings at the upland site. Error bars represent one standard error. Postharvest treatments are as follows: AS, aerial spray; AS + Burn, aerial spray followed by broadcast burning; AS + HWC, aerial spray followed banded application of herbicide.



harvesting (Fig. 3). Pine growth on MWT plots was not affected by burning, but was less than that on unburned HFBO plots (Fig. 3).

Squire et al. (1985) concluded that nutrient losses resulting from slash burning were the major reason for reduced productivity in second rotation radiata pine plantations. Subsequent studies determined that productivity losses due to nutrient removal were confined to highly infertile sites (Smith et al. 2000). Nambiar (1990) concluded that the removal of logging slash by burning increased weed competition thus reducing pine growth.

Burning did not increase the herbaceous biomass (Table 5) but may have increased the proportion of grasses (Jensen et al. 2001), which are especially competitive with planted pines (Minogue et al. 1991). Results from the upland site strengthen the conclusion that increased weed competition not soil compaction or nutrient loss was the cause of reduced growth following MWT harvesting.

At the lowland site, DAP produced a significant growth response irrespective of any other treatment (Table 7), which is not surprising, since both foliage and soil P concentrations were below critical levels (Table 1). Bedding has been reported to increase early pine growth on wet sites (Mckee and Wilhite 1986; Wilhite and Mckee 1986; Aust et al. 1998) but not on dry to intermediate sites (Mann and McGilvery 1974). At the lowland site, pine height growth was significantly reduced by the Rip–Bed treatment for the first 2 years (data not shown). During this period, growing season rainfall was below average, and increased soil drainage on Rip–Bed plots may have been detrimental to pine growth. However, at age 5 mean height and volume on Rip–Bed plots exceeds that of the other treatment plots (Table 7), suggesting that the beneficial effects of the Rip–Bed treatment may increase as the stand develops.

Conclusions

The threat to site productivity posed by mechanical whole-tree harvesting can be avoided by using appropriate mitigating treatments. However, the type and magnitude of adverse effects vary considerable, and successful mitigation requires a careful, often site-specific diagnosis and selection of mitigating treatments. For example, mechanical harvesting increased soil strength and BD considerably at the lowland site, but ambient values were low and the levels after harvesting were still below critical values for the sandy soil. Mitigating treatments such as ripping plus bedding may not have been cost-effective at this site. However, at the old-field site, ambient BD and soil strength were near critical levels prior to harvesting and a Rip–Bed treatment may have been quite beneficial. Similarly, the DAP treatment that increased growth at the lowland site may have produced a similar response at the fragipan site, where P levels were low, but at the old-field site, where P levels were adequate, it may have been better to omit the CF treatment or delay it until later in the rotation.

The impact of mechanical harvesting and site preparation may reach deeper into a soil than previously suggested. If so, a mitigation treatment that has little effect early in a rotation may prove to be highly beneficial by the end of a rotation. The effects of mechanical traffic on soil compactions may be accumulative on certain soils. Thus, continued monitoring of the current and future study sites will be necessary for the development and prescription of treatments and practices necessary to maintain site productivity.

Acknowledgments

This research was supported by a Challenge Cost Share grant from the Southern Research Station, USDA Forest Service, with additional funding and extensive cooperation from International Paper Company, Temple-Inland Forest Products Corporation and Willamette Forest Industries, Inc. Dick Fisher, Darwin Foster, Ken Farrish, Roger Williams, and

Dennis Grevatt provided valuable assistance with site selection, installation, data collection, and laboratory analyses.

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