RESPONSES OF SURFACE HYDROLOGY AND EARLY LOBLOLLY PINE GROWTH TO SOIL DISTURBANCE AND SITE PREPARATION IN A LOWER COASTAL PLAIN WETLAND*

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ABSTRACT

The effects of surface soil disturbances induced by traffic during timber harvest on surface hydrology and early pine growth were assessed after harvesting of three 19-ha, 22-year-old loblolly pine (*Pinus taeda* L.) plantations in an Atlantic coastal wetland in the south-eastern United States. This study follows previous research on surface soil disturbances caused by harvesting under dry-weather and wet-weather conditions in order to address two basic questions: (i) to what extent does the extensive surface soil disturbance on wet-weather harvested sites affect overall surface water dynamics and tree growth, and (ii) can these harvest-induced soil disturbances be mitigated through site preparation with respect to hydrologic recovery and site productivity. Overall surface hydrology and tree responses to the two harvest treatments and three site preparation levels (no preparation, bedding, or mole-ploughing + bedding) were evaluated by monitoring the water table dynamics and tree growth on a 20 × 20-m grid across the sites. The study showed that surface soil disturbances affect hydroperiod, by showing a large difference in water table elevation during the growing season between the wet-weather harvested and the dry-weather harvested sites. Bedding lowered overall surface water table initially to a large extent, but this effect decreased rapidly during the first 2 years after stand establishment. No significant differences in tree growth at age 2 were found among undisturbed, compressed, and shallow-rutted areas within non-bedded, bedded, and mole-ploughed + bedded sites. Surface deformation such as deep rutting or churning, appeared to promote tree growth on the flat-planted sites, yet showed a negative effect on early tree growth on the bedded sites. At a stand level, above-ground biomass production at this young age was little affected by surface soil disturbances.

Keywords: timber harvest; surface soil disturbance; surface hydrology; surface water table; soil productivity; forested wetlands; *Pinus taeda*.

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INTRODUCTION

Machine traffic during timber harvest inevitably causes surface soil disturbances. Apart from differences in machine types and loggers' experience, the degree and extent of the effect of harvest traffic on surface disturbance vary with soil and moisture conditions. When soils are saturated at the time of harvesting, traffic can cause a large area and broad gradient of surface soil damage. This is often the case in forested wetlands with poorly-drained soils and high water table levels, as evidenced by an extensive distribution and combination of soil compaction, rutting, puddling, or churning after timber harvest under wet-weather conditions (Aust *et al.* 1995; Aust, Burger, Carter, Preston, Patterson 1998). In the intensively-managed wetland forests of the south-eastern United States, the use of heavy machinery is a common timber harvest practice. The region's forest industry has been striving to maximise wood production while facing changing global competition and environmental regulation. This has escalated the concern over harvesting disturbance impacts on site degradation with respect to soil productivity and wetland values.

Surface soil disturbances can alter soil properties. Soil compaction usually results in an increase of bulk density and a decrease in saturated hydraulic conductivity and macroporosity (e.g., Fröhlich 1934; Soane & Van Ouwerkerk 1994; Söhne 1958). Rutting, puddling, or churning may occur under pressure of traffic when soil pore space is water-filled, which has been considered a plastic flow involving deformation at near-constant volume (Koolen 1994). This process of surface deformation has not been highly investigated and, theoretically, may not cause soil property changes if surface soils are deformed at near-constant volume as Koolen stated. Few studies, however, showed that rutting, puddling, or churning can destroy soil structure (Koenigs 1963; Gradwell 1966) and alter soil properties to such an extent as soil compaction (Aust, Burger, Carter, Preston, Patterson 1998). It can be argued that hardening of soils during rutting and churning can occur especially when subsoils are massive and compacted. In addition, rutting and churning may or may not incorporate displacement of soil organic matter, which makes it difficult to generalise rutting and churning effects on soil properties. Nevertheless, the changes in soil properties caused by all the disturbances are generally considered detrimental in terms of increasing the potential to impede site drainage and thus, to degrade site productivity. Studies on harvesting disturbance in forested wetlands usually focus on soil property changes and tree growth in compressed areas. Little is known about the impacts of harvesting disturbances on actual macrosite surface hydrology and the responses of tree growth to different surface disturbance levels.

Bedding is commonly used on wet sites in the south-eastern United States to improve tree survival and productivity. Negative effects on pine growth from bedding have been observed by some researchers: a diminution of tree growth rates during stand closure to mid rotation phases (Cain 1978; Haywood 1983; Tiarks 1983; Wilhite & Jones 1981), or a reduced survival rate (Haywood 1983). This negative effect may have been caused by limited access of roots to soil water during fast growing periods, which can occur earlier or later throughout a rotation during a dry growing season. For given climate conditions, the key factor determining bedding effect on pine growth with respect to soil water supply is overall surface water level at the sites. Traditionally, our studies emphasise improved physical conditions and drainage for root growth through bedding, but we rarely separate the change in microsite water level from the macrosite water level across the tilled area. Bedding is at the expense of soil volume loss and water table elevation in inter-bed zones. It is not clear if bedding will influence overall surface water table level, which is the dominant factor determining biological, soil physical, and chemical processes in wetlands. Bedding is also supposed to mitigate surface soil disturbances caused by harvesting (e.g., Aust, Burger, McKee, Scheerer, Tippett 1998; Burger & Pritchett 1988; Hatchell 1981; McKee & Hatchell 1986). However, some studies have observed that bedding compacted and smeared inter-bed area (Swain 1975) and did not ameliorate surface soils (Gent *et al.* 1983). Until recently, we found no report which evaluated bedding effects on overall recovery of surface hydrology following stand establishment and possibly incorporated effects on early tree growth.

This study was undertaken after previous research on harvesting impacts on surface soil disturbances (Burger 1994; Preston 1996), in order to address two basic questions: (i) to what extent do these surface soil disturbance affect overall surface water dynamics and tree growth, and (ii) can these surface soil disturbances be mitigated through site preparation with respect to hydrologic recovery and site productivity. The purpose of the study was to provide guidance for developing Best Management Practices in a region in which both maximising tree productivity and maintaining wetland values are being challenged.

MATERIALS AND METHODS

Study Area

The study was conducted in an Atlantic coastal wetland near Cottageville (32°56′N, 80°29′W) in South Carolina, United States. Average climatic data (1850–1990) collected from a nearby weather station in Charleston, South Carolina, are as follows: air temperature 19.0°C, varying monthly from 10.1°C in January to 27.6°C in July, and precipitation 1193 mm, characterised by a variation from 600 to nearly 2000 mm. Approximately, 50% of rainfall occurs during June–September. The loblolly pine plantations prior to harvesting treatments in 1994 were 22 years old, with an average tree height of 23 m and a mean volume of 371 m^3/ha. The dominant understorey species were sweetgum (*Liquidambar styraciflua* L.), elms (*Ulmus* spp.), oaks (*Quercus* spp.), green ash (*Fraxinus pennsylvanica* Marsh.), red maple (*Acer rubrum* L.), and ironwood (*Carpinus caroliniana* Walt.). The US Fish and Wildlife Service wetland inventory system (Cowardin *et al.* 1979) classified the site as Palustrine, forested, needle-leaved evergreen wetland.

The study area is within a lower coastal terrace landscape (<10 m above sea level) with a flat topography (slope <1%). Soils are derived from Oligocene and Pleistocene marine and fluvial deposits. The predominant soil series, Argent, is among hydric soils within the Alfisol order (United States classification). Soils show a sequence of A-E-Btg horizons with a large variation in depths (Fig. 1) from 0 to 51 cm (13 cm on average) for the sandy loam textured A-horizon and from 0 to 81 cm (15 cm on average) for the E-horizon with the same soil texture. Bulk density and saturated hydraulic conductivity vary greatly across the horizons (all values in median followed by ranges): 1.10 g/cm^3 (0.68–1.67 g/cm^3) and 7.71 cm/h (0.00–99.99 cm/h) for the A-horizon; 1.66 g/cm^3 (1.20–1.87 g/cm^3) and 0.175 cm/h (0.00–23.67 cm/h) for the E-horizon, respectively. The sandy clay texture Btg-horizon that can appear from the soil surface is massively compacted with a bulk density (median) of 1.51 g/cm^3 (0.93–1.81 g/cm^3) and a saturated hydraulic conductivity (median) of 0.00 cm/h (0.00–7.09 cm/h). Monthly means of the surface water table depths (1992–1998) at the site are highest during December and March (<35 cm below soil surface) and lowest during April and May (>65 cm below soil surface) (Xu *et al.* 1999).

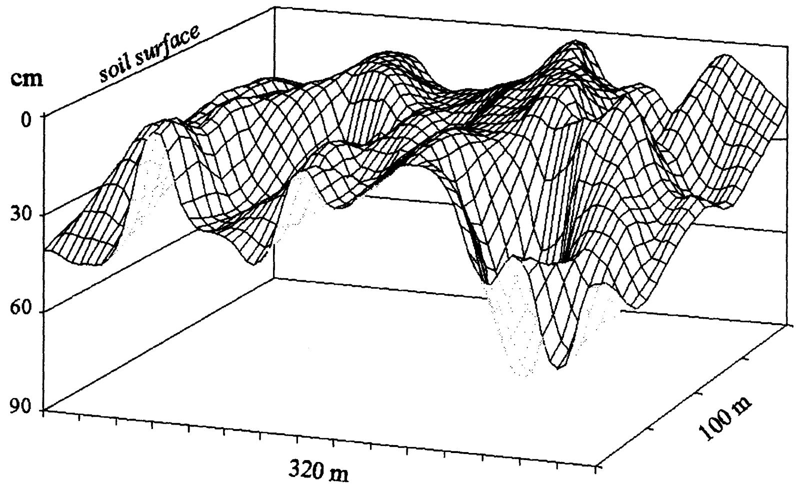

FIG. 1–Depths of Btg-horizon in an experimental plot, showing a strong spatial variation of soils at the study sites.

Experimental Design and Measurements

Two harvest treatments (wet-weather and dry-weather harvesting) and three site preparation levels (no preparation, bedding, and mole-ploughing + bedding) were randomly assigned to six subdivided treatment plots (each 3.2 ha) in each of the three plantations. Harvesting was carried out under two soil moisture conditions: (i) when surface soils were dry (θ 10–15%) during the fall of 1993 (dry-weather harvest), and (ii) when surface soils were nearly saturated (θ 30–40%) during the spring of 1994 (wet-weather harvest). Harvesting was performed using rubber-tyred feller-bunchers (Hydro-Axe 411, Blount Inc., Owatonna, Minnesota, USA; Franklin 105, Franklin Equipment, Franklin, Virginia, USA) and medium-sized grapple skidders (Franklin 170; Caterpillar 518, Caterpillar Inc., Peoria, Illinois, USA; Timberjack 450C, Timberjack Group, Helsinki, Finland) with 81.3-cm-wide tyres exerting an inflation pressure between 207 and 241 kPa. Bedding on a 3-m spacing was performed in November 1995, using a 6-disc bedding plough equipped with 91.4-cm discs (Model 110, Savannah Forestry Equipment Inc., Savannah, Georgia, USA). In the mole-plough + bed treatment, a 10-cm-diameter channel was created at a 70–80 cm depth on a 20 × 20-m grid prior to bedding, by using a modified deep plough device consisting of a 1-m-long shank and 50-cm plough. Bedding and mole-ploughing implements were pulled with a caterpillar D-8 tractor. All plots were hand-planted in February 1996, using genetically improved loblolly pine seedlings provided by Westvaco Corporation, South Carolina, USA.

The basic scheme for all data collection was a systematic grid of 20 × 20 m crossing the study sites. Polyvinyl chloride pipes (n=1409) were installed on each grid point to monitor monthly changes in surface water table for five periods: (i) pre-harvest (May 1992–July 1993); (ii) post-harvest (July 1994–July 1995); (iii) post-site-preparation (February–April 1996); (iv) first year after stand establishment (May 1996–April 1997); and (v) second year after stand establishment (May 1997–April 1998). A surface disturbance survey on each grid point after harvesting was conducted (Preston 1996) by visually classifying surface soil disturbances in: (i) undisturbed (SD1), (ii) compressed (SD2), (iii) shallow-rutted (<20 cm) (SD3), (iv) deep-rutted (>20 cm) (SD4), and (v) churned (SD5). Tree growth at age 2 was measured in a circular 1/125-ha sampling plot centred on each grid point. Above-ground biomass was estimated using the regression functions developed by Kelting (unpubl. data) based on the tree base diameter and height in 54 bioassay plots (2.1 × 6.3 m) (Kelting 1999) at our study sites.

Data Analyses

Monthly water table depths were averaged at the plot level for each of the five sampling periods. Our pre-harvest water data, measured over a 1-year period, showed a difference in depth to water table between the uncut control plots and the treatment plots which ranged from –5 to 12 cm. This site effect and the results of pre-harvest water table have been discussed by Xu *et al.* (1999). This difference, found during the pre-harvest measurement period, was used as an adjustment factor, β, in order to remove site effects among treatments. Relative changes in water table depths (Δ) by treatment were then calculated as follows:

$$\Delta = WT\_Treat_{i,j} - WT\_Ref_{i,j} \pm \beta \qquad (1)$$

where *WT_Treat* and *WT_Ref* are the mean water table depths for the treatment and uncut reference plots respectively and *i* and *j* represent each treatment block and sampling period. The calculated relative changes in water table depth were used only for the ANOVA test of treatment effect on site hydrology.

Averages of actual water table depths over the 2-year stand establishment period were used for regression analyses to investigate how tree growth responds to changes in water table depth. ANOVA analysis was also employed to test harvesting disturbance and site preparation effects on soil physical properties and tree growth. If significant differences were revealed at an alpha of 0.1, Duncan's multiple range test was used for mean separation. All statistical procedures were performed using the SAS software package (SAS Institute Inc. 1988).

RESULTS AND DISCUSSION

Harvesting Impacts on Surface Soil Disturbance

Preston (1996) reported a large area and a broad gradient of surface soil disturbances caused by wet-weather harvesting at our study sites. Although the surface disturbance was spatially very heterogeneous (data not presented), on average, 92% of the dry-weather harvested sites remained undisturbed, whereas 77% of the wet-weather harvested sites were compressed, rutted, puddled, or churned (Fig. 2). Based upon these disturbance percentages and the changes in soil physical properties in five disturbance classes (Aust, Burger, Carter, Preston, Patterson 1998), changes in bulk density, saturated hydraulic conductivity, macroporosity, and total porosity were estimated for the dry-weather and wet-weather harvested sites (Table 1). The result shows that on the wet-weather harvested sites, saturated hydraulic conductivity, macroporosity, and total porosity decreased 72%, 44%, and 8%, respectively, and bulk density increased 19%. In contrast, the changes of these properties on the surface of the dry-weather harvested sites were much smaller (in the same arrangement and direction): 6%, 3%, 1%, and 2%.

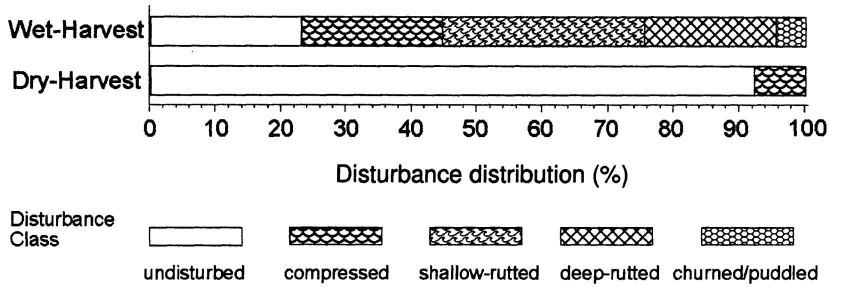

FIG. 2–Surface soil damage after harvesting of three wetland pine plantations under wet-weather and dry-weather conditions (data adapted from Preston 1996).

TABLE 1–Changes in water-related soil properties after harvesting of three wetland pine plantations under dry-weather and wet-weather conditions.

Treatment	Bulk density (g/cm^3)	Hydraulic conductivity (cm/h)	Macro porosity (%)	Total porosity (%)
Dry-harvest	+0.02 b* (1.17)	–0.66 a (10.65)	–0.35 a (13.10)	–0.48 a (54.54)
Wet-harvest	+0.22 a (1.17)	–8.85 b (12.22)	–7.21 b (16.22)	–4.09 b (53.06)

* Means followed by the same letter within a column are not significantly different at the 0.1 level. Values in parentheses are means prior to harvesting.

Koolen (1994) summarised three general types of soil behaviour under wheel pressure:
(i) non-deforming—wheel-induced soil stresses are low relative to soil strength;
(ii) hardening—wheel-induced soil stresses exceed soil strength; and
(iii) plastic flow—involving deformation at near-constant volume.

For a given tyre pressure, traffic speed, and frequency, the behaviour of a soil with certain texture and organic content under traffic pressure should be subject to its moisture condition. At our study sites, a similar small portion of compression was found on all dry-weather harvested sites, whereas a large spatial variation of compression, rutting, and churning occurred on all wet-weather harvested sites. The horizon depths of the soils on the sites are highly variable and the fact that the massive Btg-horizon varies locally from the soil surface to 81 cm depth (Fig. 1) may have influenced the variation and distribution of soil disturbances during the wet-weather harvest. This implies that the types and degrees of surface soil disturbance, potentially caused by timber harvest, may be predictable, and that such a prediction, especially for a wet-weather harvest, requires more detailed information on spatial patterns of soils.

Surface Hydrology Responses to Harvesting Disturbance and Site Preparation

During a 1-year post-harvest period (July 1994–July 1995), average water table depths were elevated 14 cm for the dry-weather harvested sites and 21 cm for the wet-weather harvested sites compared to the uncut control plots (Table 2). This difference in water table

TABLE 2–Relative changes in surface water table (calculated using Equation 1) as affected by harvesting and site preparation treatments.

Treatment		Elevation in water table depths (cm)			
		Post-harvest*	Post-site-preparation	1 year	2 years
Dry-harvest	Non-bed	14 b	43 a	28 b	14 ab
	Bed		28 b	25 b	13 b
Wet-harvest	Non-bed		45 a	36 a	21 a
	Bed	21 a	27 b	28 b	16 ab
	Plough+bed		27 b	30 b	18 ab

* Post -harvest = July 1994–July 1995; Post-site-preparation = February–April 1996; 1 year after planting = May 1996–April 1997; 2 years after planting = May 1997–April 1998.
Means followed by the same letter within a column are not significantly different at the 0.1 level.

elevation between the two harvest treatments was very small during the dormant season (<2 cm), but large during the growing season (>10 cm) (Fig. 3). This difference remained 2 years after tree planting on the non-bedded sites (Table 2). Bedding, both conventional and mole-plough bedding, initially lowered overall surface water table depths on the dry-weather and wet-weather harvested sites. During the short post-site-preparation period (end of February–beginning of April 1996), the bedded sites showed a 15–18 cm lower water table depth than the non-bedded sites. However, in the 2 years after tree planting, conventional

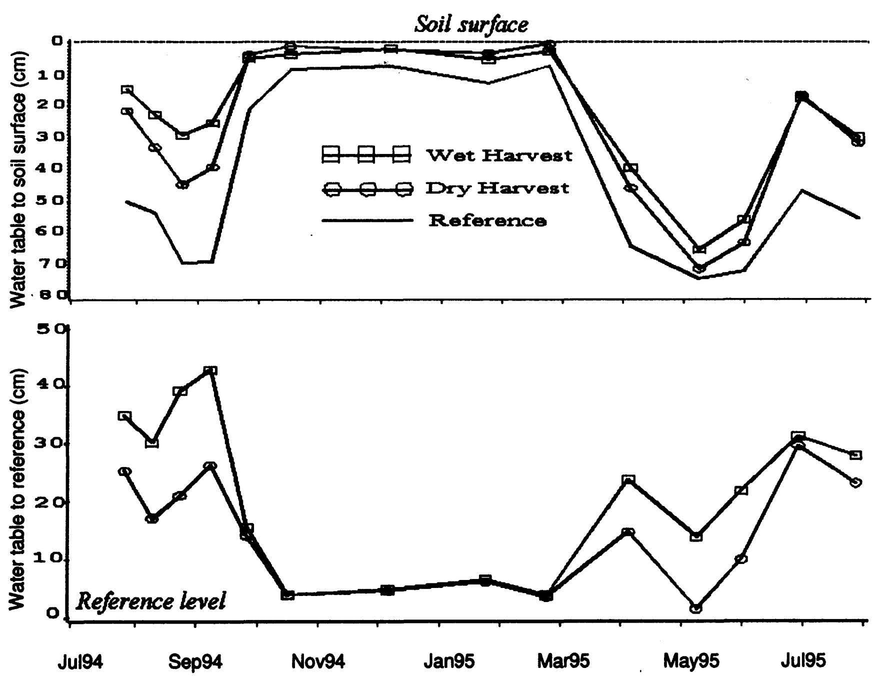

FIG. 3–Surface water table dynamics as affected by harvesting treatment during the first year after harvesting: actual water table (above) and relative changes in water table (below, calculated using Equation 1).

bedding and mole-ploughing + bedding did not prove to have a lasting effect in lowering overall surface water table. Throughout stand establishment, the water table was higher on the wet-weather harvested sites than on the dry-weather harvested sites with or without bedding treatments (Table 2). Although this difference was not statistically significant, the trend suggests a faster recovery of surface hydrology on the dry-weather harvested sites with minimal surface soil disturbances.

Elevation in surface water table after harvesting has also been observed on a tupelo-cypress wetland (Aust & Lea 1992), a floodplain (Lockaby *et al.* 1997), and a blackwater bottomland (Perison *et al.* 1997) in the south-eastern United States. Our results support the statement that the most common hydrologic change following harvesting of a forested wetland is the elevation of surface water table depths. Furthermore, our study shows that this change was small during the dormant season, but large during the growing season (Fig. 3), indicating an alteration in hydroperiod after harvesting. The magnitude of this alteration in hydroperiod is clearly reflected in harvesting disturbances, by showing that the water table on the wet-weather harvested sites with a high portion of disturbed area was elevated by more than 10 cm higher than that on the dry-weather harvested sites with minimal surface compression. Several researchers found that harvesting greatly reduced woody species in ground vegetation communities (Conde *et al.* 1983; Stransky *et al.* 1986; Swindel *et al.* 1989). At our study sites, Lister (1999) observed that the disturbed areas had considerably lower biomass of woody species (mostly <20%) than the undisturbed areas (>55%) in the total dominant non-crop biomass. The large difference in water table between the harvesting treatments during the growing season should thus be attributed to the change in vegetation community that can influence evapotranspiration rate. The small difference in water table elevation between the two harvest treatments during the dormant season suggests that overall site drainage is little affected by the changes in soil physical and hydraulic properties caused by harvesting disturbances. This may be particularly true because poorly drained soils on wet pine flats appear to be less vulnerable to harvesting disturbances than well-drained soils, as observed in other studies (e.g., Aust *et al.* 1995).

Both conventional bedding and mole-ploughing + bedding showed a short-term effect on overall surface water table in this study. Bedding manipulates microsite topography at the expense of soil volume loss in inter-bed zones. The lowered areas can provide a large space for water storage, which explains the radical separation in overall surface water table depths following bedding (Table 2). However, except for the wet-weather harvested sites without bedding, there was no significant difference in overall surface water elevations between bedded sites and flat planted sites during the stand establishment period, indicating that a new equilibrium of overall surface water table across the sites had been created. Horton *et al.* (1994) stressed that any use of tillage tools (tyres, sliding plates, discs) can produce a zone of soil compaction below the depth of device action, which may complicate soil drainage in the inter-bed area. This may be of special importance for the sites with flat topography and impermeable subsoils. Currently no theoretical basis exists for predicting soil properties from use of a tillage tool alone or in combination with different tillage tools (Hadas *et al.* 1988; Horton *et al.* 1994). But the fact that the water table depths on dry-weather harvested sites without bedding showed the fastest hydrologic recovery throughout the 2-year period of stand establishment, suggests that bedding is an additional disturbance with regard to overall surface hydrology.

Tree Growth Responses to Harvesting Disturbance and Site Preparation

Because of the small percentage (<5%, Fig. 2) and heterogeneous distribution of churned areas among the treatment plots, tree growth data for this disturbance class (SD5) were merged with those from the deep-rutted areas (SD4). The growth rates in height, dbh (diameter at breast height), and above-ground biomass are summarised by disturbance classes in Table 3. Tree height was selected as a dependent variable to surface water table depths by disturbance in regression analysis (Fig. 4).

TABLE 3–Early tree growth responses to harvest-induced soil disturbances on non-bedded (Flat), bedded (Bed), and mole-ploughed+bedded (MPB) sites.

Disturbance class	Height (cm)			dbh (cm)			Above-ground biomass (g/tree)		
	Flat	Bed	MPB	Flat	Bed	MPB	Flat	Bed	MPB
SD1	138.3 a	192.3 a	216.3 a	1.1 ab	1.7 a	1.9 a	238.2 b	634.2 a	856.6 a
SD2	130.1 a	199.5 ab	209.0 a	1.0 b	1.8 a	1.9 a	227.6 b	692.8 a	838.5 a
SD3	126.9 a	186.7 ab	210.8 a	1.1 ab	1.6 a	1.9 a	245.8 b	602.2 a	851.9 a
SD4	140.6 a	168.3 b	184.6 b	1.2 a	1.5 a	1.7 b	319.8 a	526.1 a	678.3 b

* Disturbance classes based on a visual surface survey after harvesting: SD1 = non-disturbance; SD2= compression; SD3=shallow rutting (<20 cm); and SD4=deep rutting (>20 cm) and churning.
Means followed by the same letter within a column are not significantly different at the 0.1 level.

No significant difference in tree growth among undisturbed, compressed, and shallow-rutted areas was found on non-bedded, bedded, or mole-ploughed + bedded sites. Deep-rutting and churning seemed to promote early pine growth on the flat-planted sites by showing the highest growth rates in above-ground biomass, tree height, and dbh (Table 3). On the bedded sites (both conventional and mole-ploughed + bedded), however, the deep-rutted and churned areas exhibited the lowest growth rates.

Root growth may be restricted from compressed soils due to mechanical and water supply limitations. Therefore, changes in bulk density by surface soil compression during harvesting are considered one of the main factors for site degradation (e.g., Dickerson 1976; Froehlich & McNabb 1984; Greacen & Sands 1980). Rutting may incorporate removal of soil organic matter (Burger & Kelting 1998), which can alter soil properties and nutrient availability. In our study, however, none of the tree growth rates (height, dbh, and above-ground biomass) was significantly different among undisturbed, compressed and shallow-rutted areas. Our tree growth data were collected on circular sampling plots (1/125 ha), centred on each 20 × 20-m grid point. Within a sampling plot microsite soil and water conditions may have been largely changed by harvesting disturbances, as evidenced by the drastic changes of responses in tree height to the surface water table depths in different disturbance classes (Fig. 4). Despite a large variation, on the undisturbed (SD1) areas without bedding tree height was closely correlated to surface water table depths ($r^2 = 0.41, p = 0.0001$). This relationship follows the general parabolic response of tree growth to soil moisture from wet to dry condition, as illustrated by Hansen (1977). In contrast, no relationship between tree height and surface water table depths could be found on the disturbed areas. The trend indicates an

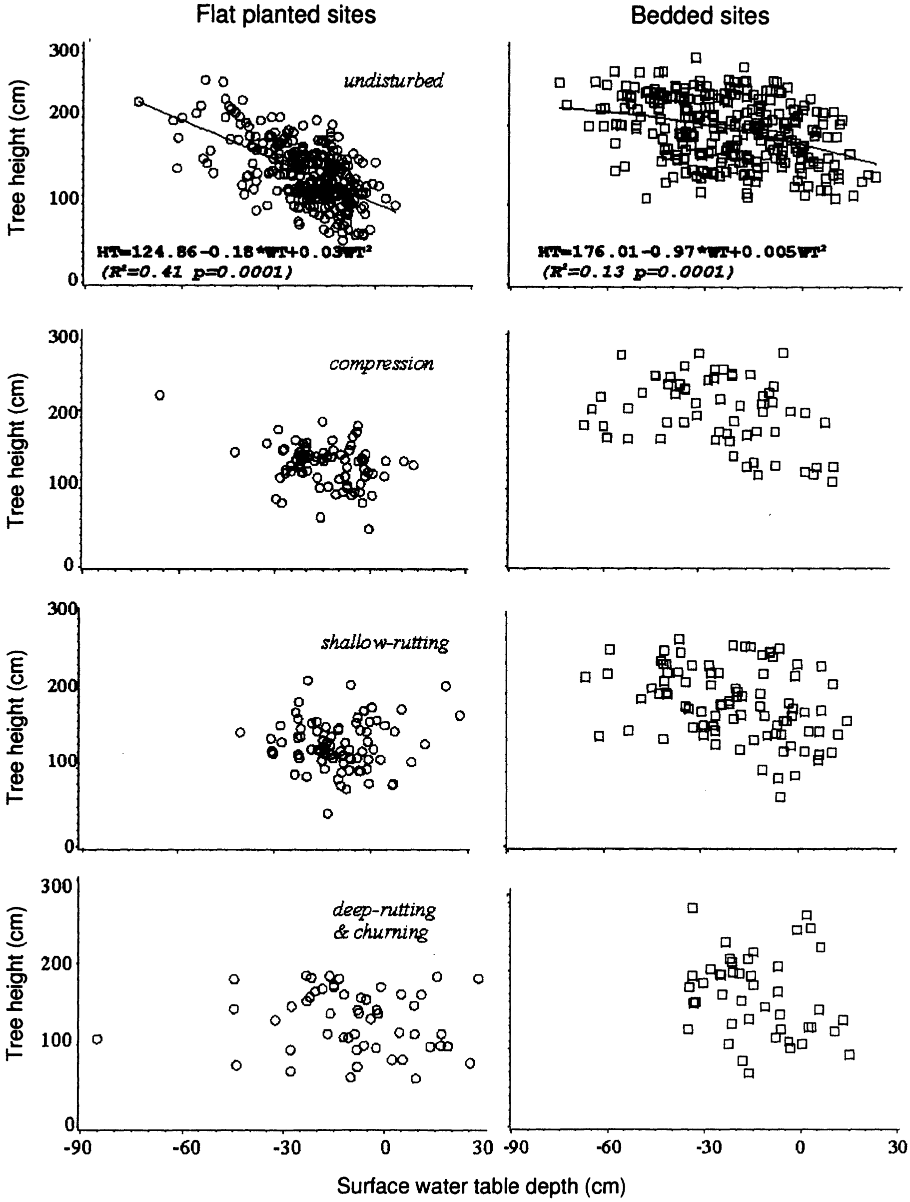

FIG. 4—Responses of early loblolly pine height growth to surface soil disturbances across a gradient of surface water table depths.

increasing chaos and variation, by showing that on the rutted areas tree growth can be negatively affected but also positively affected by harvesting disturbance. The positive effect may have been caused by improved access of roots to soil water when trees are planted on elevated areas caused by surface change during harvesting. This is shown by the fact that growth of trees on the deep-rutted areas exceeded those on the undisturbed, compressed, and shallow-rutted areas, implying that deep-rutting (of wetland soils) can act like bedding and thus must not be always negative with respect to early tree growth.

It is widely acknowledged that bedding wet sites improves soil water and aeration conditions by elevating trees on beds from the surface water level. This site preparation method has also been used to mitigate surface soil disturbances caused by harvesting (e.g., Aust, Burger, McKee, Scheerer, Tippett 1998; Burger & Pritchett 1988; Hatchell 1981; McKee & Hatchell 1986). In our study, pine growth rates on all disturbance levels were largely increased by bedding (Table 3), but complete mitigation of the surface disturbances is uncertain. Bedding consistently elevated tree height growth across the undisturbed and compressed areas, but only partially across the rutted and churned areas (Fig. 4). In fact, tree height, dbh, and above-ground biomass were lowest in the deep-rutted and churned areas within bed treatments (Table 3). This indicates a limitation of bedding effects in extensively disturbed areas. The deep-rutted areas have either diminished bedding quality or not been mitigated through bedding. In opposition to mitigation, bedding exhibited an effect of surface soil disturbance, by showing an enlarged variation in tree growth especially on the undisturbed areas (Fig. 4): tree height to surface water table on the undisturbed, bedded areas was much looser ($r^2 = 0.13$) than that on the undisturbed, non-bedded areas ($r^2 = 0.41$).

Stand Productivity by Harvesting and Site Preparation

No significant difference in above-ground biomass production was found at the stand level between the dry-weather harvested and wet-weather harvested sites with or without a conventional bedding treatment (Table 4). The wet-weather harvested sites, both non-bedded and bedded, showed a slightly higher stand biomass than the dry-weather harvested sites, and this was due to a higher tree stocking and average biomass of each single tree. Bedding increased above-ground biomass production, but showed a negative effect on tree survival. Mole-ploughing + bedding increased above-ground biomass by 50% over that of conventional bedding, although mole-ploughing + bedding did not produce a significantly lowered water table compared to conventional bedding (Table 2).

In this study, pine above-ground production at this young age did not appear to be affected by harvest treatments at the stand level. Considering that the surface disturbances induced a large variation in tree growth as mentioned in the previous section, this result does not mean that harvesting disturbance had no effect on early pine growth. Tree height responses are shown in Fig. 5 as a function of surface water table by harvest and site preparation treatments. Tree height on the dry-weather harvested site without bedding showed the closest relationship

TABLE 4—Early tree growth responses to harvesting disturbance and site preparation at a stand level.

Treatment		Tree survival (%)	Stocking (trees/ha)	Above-ground biomass (g/tree)	Above-ground biomass (kg/ha)
Dry-harvest	Non-bed	91 a	1637 b	234.0 c	381.5 c
	Bed	79 c	1556 b	599.3 b	956.1 b
Wet-harvest	Non-bed	92 a	1706 b	259.0 c	442.1 c
	Bed	80 c	1599 b	647.5 b	1031.6 b
	Plough+bed	86 b	1868 a	815.1 a	1535.3 a

Means followed by the same letter within a column are not significantly different at the 0.1 level.

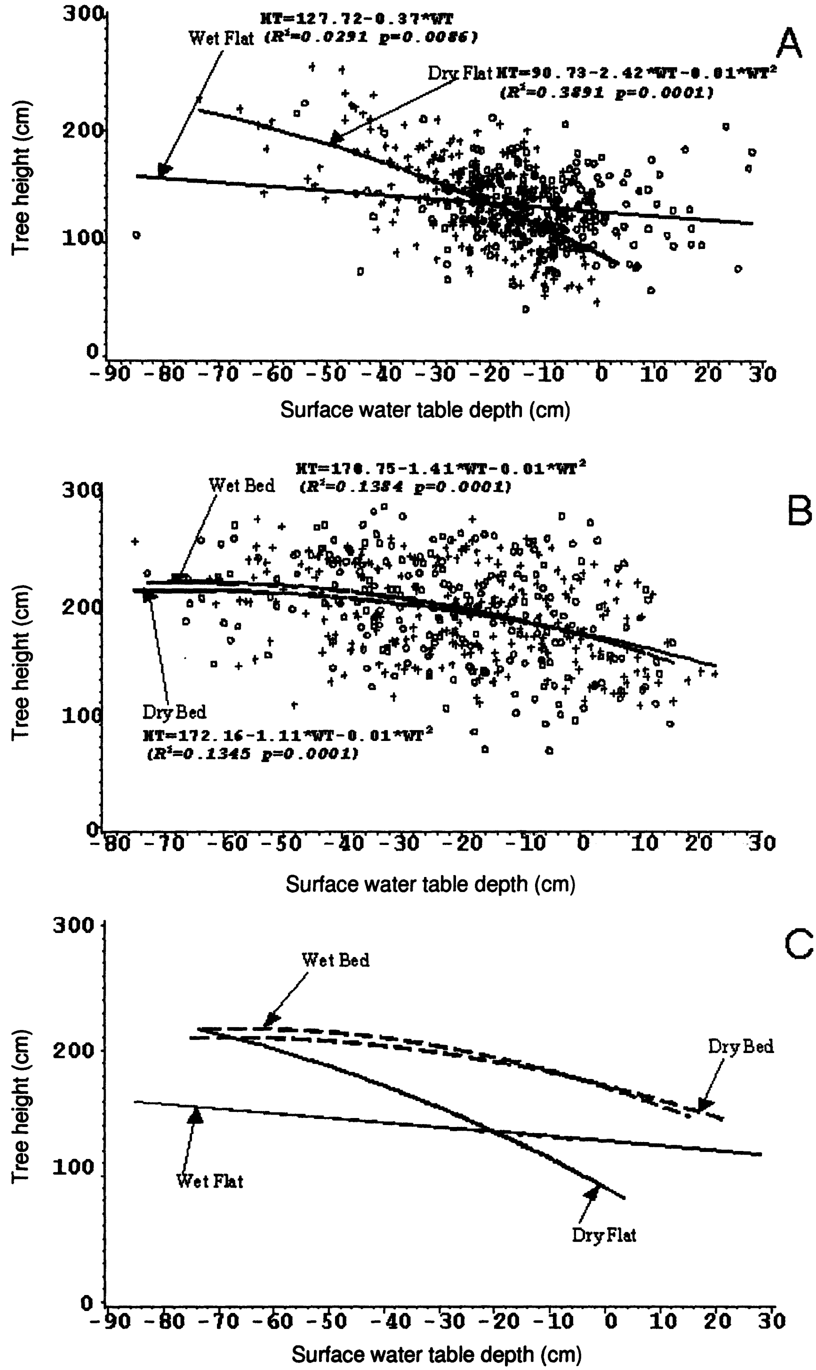

FIG. 5–Early height growth of loblolly pine as a function of surface water table depths by harvest and site preparation treatment: (A) flat-planted and (B) bedded sites harvested under dry-weather (Dry Flat, n=236 and Dry Bed, n=229, plus) and wet-weather (Wet Flat, n=235 and Wet Bed, n=232, circle) conditions.

with surface water table (Fig. 5a), which, more or less, obeys the natural principle that tree growth from an optimum soil moisture condition decreases with increasing wetness and drought. Wet-weather harvesting complicates this relationship by shifting a large number of sampling plots from a lower surface water table to a higher surface water table, as well as by creating a greater variation of tree height growth response to water table depth. At a stand level, this actual effect of harvest treatments is concealed. It is crucial to know if this spatial pattern caused by harvesting disturbance will remain, and how it will affect tree production at the stand level through the end of a rotation.

Numerous studies have shown the beneficial effects of bedding on early pine growth due to better aeration conditions (e.g., McKee & Shoulders 1970; Terry & Hughes 1975), nutrient availability (Burger & Pritchett 1984, 1988), and vegetation competition (e.g., Cain 1991; Miller *et al.* 1991; USDA Forest Service 1984). In our study, above-ground biomass production at the stand level was doubled by conventional bedding and tripled by mole-ploughing + bedding. This productivity increase was due mainly to bedding of the undisturbed and less-intensively-disturbed areas (compressed or shallow-rutted), as the lowest above-ground biomass was in the deep-rutted area at the bedded sites (Table 3). In this regard, bedding did not fully mitigate surface soil disturbances caused by wet-weather harvesting.

Furthermore, this study showed that the bedding effect on pine growth on wet sites may be predictable. When the response curves of tree height by harvesting and bedding treatments are superimposed (Fig. 5a, b), it shows that bedding mainly increases tree height in the areas within a shallow water table range (Fig. 5c). Considering the tree height response function on the dry-weather harvested site as a baseline, it appears obvious that the beneficial effect of bedding on tree height decreases with increasing water table depths. This benefit ceases as the response curves join at a deeper water table level (about 65 cm). The bedding effect on tree height then, is represented as the area between the response curves on flat-planted and bedded sites. Theoretically, any gain in tree growth through bedding across a gradient of surface water table levels, regardless of height, volume, or biomass, can be formulated as follows:

$$\Delta = \int_a^b f(w)\,dw - \int_a^b g(w)\,dw = \int_a^b [f(w) - g(w)]dw \qquad for\ a \le w \le b;\ f(w) \ge g(w) \qquad (2)$$

where w is the surface water table depth, $f(w)$ is the growth function for bedded sites, $g(w)$ is the growth function for non-bedded sites, and a and b are the range of surface water table from the highest to the crossing point of the two response functions. Although tree growth is a combined result of genetic resources, soil water and nutrient availability, climate conditions, and management practices that can modify those variables, the strategy of this formulation can be useful for simply estimating potential bedding effect on pine growth on wet sites.

CONCLUSIONS

Harvesting and harvest-induced surface disturbances affected hydroperiod on a pine flat by elevating surface water table depths during the growing season. Changes in soil physical and hydraulic properties caused by surface disturbances had little effect on overall site drainage. Bedding did not lower the overall surface water table after stand establishment, nor fully mitigate soil disturbances with respect to early pine growth. No significant difference in early pine growth, except for deep-rutting and churning, was found among surface soil disturbances. The disturbances appeared to cause a large microsite variation in pine growth due to the fact that the early pine growth was both negatively and positively affected by surface disturbances, apparently through manipulating microsite topography and diminishing vegetation competition. Thus, above-ground biomass production at the stand level was concealed and appeared not affected by harvesting treatment. It is particularly debated if soil water and nutrient resources will be restricted by soil disturbances during stand closure and mid rotation phases, in which tree roots explore more soil volume. This, in fact, creates two questions: (i) what processes and relations between disturbed and undisturbed microsites interact with respect to soil water, aeration, and nutrient availability, and (ii) if and how these processes will influence pine growth through time at a stand level. Spatial analysis and long-term observation on the dynamics in surface water and tree growth are necessary to answer these questions.

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