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# Soil strength response of select soil disturbance classes on a wet pine flat in South Carolina

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## Abstract

Harvest operations conducted under conditions of high soil moisture on a wet pine flat in South Carolina resulted in a high degree of soil surface disturbance. Less soil surface disturbance occurred when soil moisture content was lower. Soil strength varied by soil disturbance class in wet harvested locations and highly disturbed areas were associated with low soil strength and elevated levels of soil moisture. Soil strength levels in untrafficked locations were significantly higher than more disturbed classes including ruts greater than 0.20 m and puddled soils. The application of bedding to both wet and dry harvested locations lowered soil strength to less than 1.0 MPa in the upper 0.40 m. Mole plowing, in general, did not appear to have a significant impact on soil strength under the conditions of this study. However, soil strength of untrafficked areas increased when subjected to mole plowing. This may be the result of lowering soil moisture status and subsequently increasing soil strength in response to drier soil conditions. Further elaboration on the relationship among soil strength, disturbance conditions and machine trafficking is necessary to fully understand this complex interaction.
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*Keywords:* Harvest; Bedding; Wet pine flat; Coastal Plain; Mole plowing; Loblolly pine; Disturbance classes

## 1. Introduction

Wet pine flats are found extensively throughout the southeastern United States and are characterized by flat terrain, a water table in close proximity to the soil surface and poor drainage (Clewell and Lea, 1990). Wet pine flats have been used extensively for loblolly pine (*Pinus taeda* L.) production and their importance in future production is expected to increase (Burger et al., 1995). Significant soil surface disturbance occurs as machine traffic traverses wet flats due to the low bearing capacity that results from high soil moisture contents and low soil strength. This condition has led to the occurrence of compacted, rutted, and puddled soils concomitant with a loss of soil physical structure and function that has been linked to lowered site productivity (Hatchell et al., 1970; Burger et al., 1989; Aust et al., 1993, 1995).

Mitigation of soil damage as a result of harvesting can be accomplished through site preparation operations that manipulate the surface and subsoil layers for improved surface drainage, reduced soil strength to increase root proliferation, and increased nutrient availability (Allen et al., 1990). Survival and increased productivity of loblolly pine on lower Coastal Plain sites have been reported after bedding of harvested wet pine flats, especially on poorly drained sites (McKee and Wilhite, 1986). However, lowered productivity of loblolly pine is still reported on severely impacted sites and may be indicative of the limited ability of mechanical methods of site preparation to restore soil physical conditions to levels necessary for productive growth (Lockaby and Vidrine, 1984; Scheerer et al., 1995). Changes in soil physical properties in response to intensive management have been linked to changes in chemical, biological and hydrological properties and processes that may impede long term site productivity (Tiarks and Haywood, 1996; Kelting et al., 1999).

The response of harvested sites to trafficking and subsequent recovery by site preparation may be determined by measuring soil strength, expressed as cone index or penetration resistance. Soil strength has served a dual purpose in soil studies as a sensitive indicator of site susceptibility to machine trafficking, e.g. soil compaction, as well as an indication of a site's ability to

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support adequate crop and root growth (Taylor and Gardner, 1963; Russell and Goss, 1974; Greacen and Sands, 1980; Ayers and Perumpral, 1982; Burger et al., 1995). Soil strength determinations are conducted by inserting a cone penetrometer into the ground at a specific rate and the resistance exerted by the soil recorded: the greater the resistance, the higher the soil strength. Soil strength measurements are influenced primarily by soil moisture content, bulk density, and soil texture. Ayers and Perumpral (1982) noted that peak soil strength occurred at varying soil moisture content depending on soil textural condition, e.g. less moisture was required in a coarse soil. Soil strength levels have been noted to increase in response to increased bulk density, the degree of change dependent on soil moisture condition (Sands et al., 1979; Ayers and Perumpral, 1982; Smith et al., 1997).

Early researchers noted an inverse relationship between soil strength and root growth of select agricultural crops, citing it as more relevant than bulk density as an indication of restricted root growth (Taylor and Gardner, 1963; Russell and Goss, 1974). Soil strength levels reported as restricting root growth of cotton (*Gossypium hirsutum*) ranged between 2.0 and 2.5 MPa for fine textured soils and 6.0 MPa in coarser textured soils (Taylor and Gardner, 1963; Gerard et al., 1982). Soil strength levels in managed forest sites subjected to harvesting and site preparation have been previously reported (Hatchell et al., 1970; Sands et al., 1979; Lockaby and Vidrine, 1984; Aust et al., 1993; Carter et al., 2006) but a lack of information still exists. A recent report by Aust et al. (1993) noted increased soil strength in a wet pine flat in response to harvest disturbances and reported soil strengths of 0.45 and 0.625 MPa in compressed and rutted areas, respectively, versus 0.425 MPa in undisturbed areas. Even less data are available that identify root limiting soil strength levels in managed forests (Sands et al., 1979).

The objective of the study was an assessment of soil strength variations in soil surface disturbance classes tabulated on a wet pine flat harvested under two soil moisture conditions and a comparison with soil strength response of previously identified disturbance classes altered by site preparation.

## 2. Materials and methods

### 2.1. Study site and environs

The study site is located on the lower Coastal Plain of the southeastern U.S. in Colleton County, South Carolina, an area of low lying elevations (3–10 m above MSL) on marine and fluvial deposits of the Pamlico Terrace. Mean annual precipitation is 132 cm while mean winter and summer temperatures are 18 and 31 °C, respectively (Stuck, 1982). The study site is dominated by two soil series: Argent loam (fine, mixed, thermic Typic Ochraqualf) and Santee loam (fine, mixed, thermic Typic Argiaquolls), members of the Alfisol and Mollisol soil orders; to a lesser degree, the Hobcaw (fine-loamy, siliceous, thermic Typic Umbraquults) and Nemours (clayey, mixed, thermic Aquic Hapludults) soil series, members of the Ultisol soil order (Stuck, 1982). Soils within the area were derived from unconsolidated sands, clays and limestone. The soils are mapped as a single unit and are generally poorly drained with slow to moderate permeability. The study site supported a 20-year-old loblolly pine stand with an understory layer of red maple (*Acer rubrum*), water oak (*Quercus nigra*), willow oak (*Q. falcata* var. pagodifolia), sweetgum (*Liquidambar styraciflua*), and palmetto (*Sabal* sp.). The site is owned and operated by MeadWestvaco of Summerville, South Carolina.

### 2.2. Experimental design

The experimental design consisted of a randomized block design with a split plot replicated three times with two levels of logging disturbance: high soil moisture versus low soil moisture, three methods of site preparation: none, bedding, bedding and mole plowing and disturbance class as the split plot. Treatment combinations in each replication consisted of wet harvesting and no site preparation (flat planted) (WFP), wet harvesting and bedding (WB), wet harvesting and bedding/mole plowing (WMB), dry harvesting and no site preparation (flat planted) (DFP) and dry harvesting and bedding (DB).

### 2.3. Methods

The study area was approximately 57.6 ha in size, divided into three replications (blocks) approximately 19 ha in size and each replication subdivided into six 3.2 ha plots (Fig. 1). Operational harvesting treatments were randomly applied to five of the six plots while one plot served as a non-harvested control (CON). Two plots in each replication were harvested in September 1993 when VWC was limited to less than 15% (approximately 12%) and three in each replication were harvested in March 1994 when volumetric water content (VWC) exceeded 30% (approximately 34%); these are termed dry harvested and wet harvested, respectively. Study blocks were selected based on similarities in drainage conditions and soil types. Harvesting was performed by the use of feller-bunchers (Hydro-Ax 411, Blount, Inc., Owatonna, MN; and Franklin 105, Franklin Treefarmer, Franklin, VA) and wide-tired (81.3 cm) skidders (Franklin 170 and Caterpillar 518, Caterpillar Inc., Peoria, IL). Mole plowing was selected as a method of site preparation as a means of controlling water table elevations in saturated sites of high clay content (Robinson et al., 1987). Mole plowing was conducted in October 1995 on a 20 m × 20 m grid pattern to a depth of 80 cm to facilitate water movement through the $B_t$ soil horizon. Bedding was installed in November 1995 using a Savannah 110 (Savannah Forestry Equipment, LLC, Savannah, GA) bedding plow after shearing and drum chopping. Site preparation activities that commenced in Fall of 1995 were conducted when VWC was approximately 46%. The site was hand planted in February 1996 with genetically improved loblolly pine stock.

Soil surface disturbance classes were selected prior to harvesting and tabulated for each harvested plot prior to site preparation. Surface disturbance classes of wet harvested sites included untrafficked (UNT), compression tracks (COMP)

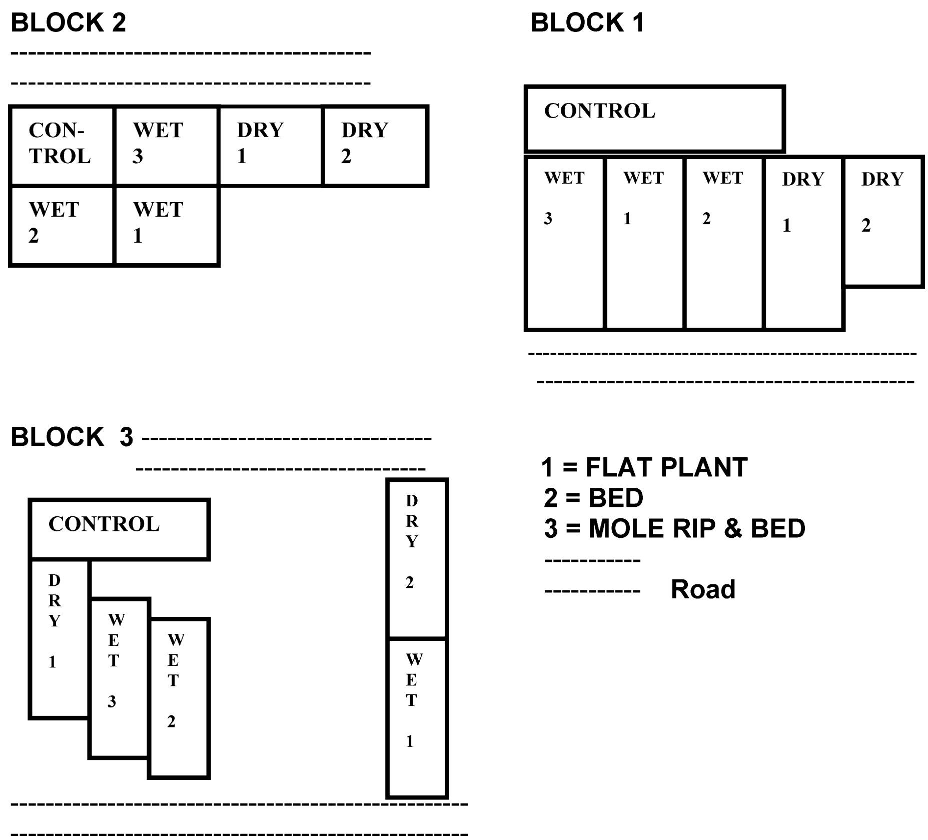


Fig. 1. Plot layout of study to examine the impact of harvest operations in a wet pine flat in South Carolina conducted at two levels of soil moisture and subjected to three levels of site preparation.

defined as evidence of trafficking, ruts less than 0.20 m (RUT1), ruts greater than 0.20 m (RUT2), and churned or puddled soils (PUD). Two classes were tabulated in the dry harvested sites: untrafficked (UNT) and compression tracks (COMP). Soil disturbance classes were tabulated and reported by Preston (1996) for 80 points within the treatment blocks. Soil disturbance classes selected for evaluation in the overall study represent disturbances typically observed when harvesting on wet pine flats and are noted by state inspectors in South Carolina for compliance with Best Management Practices (BMPs), especially the occurrence of ruts greater than 0.20 m (Aust, personal communication, 1997).

Soil strength expressed as cone index (CI) and VWC measurements were collected in December 1995 and January 1996 after completion of site preparation activities and prior to planting of seedlings. Three or more sampling points in each treatment plot that corresponded to each disturbance class were relocated in both flat planted and sites subjected to site preparation to measure penetrometer resistance and water content. In the case of flat planted sites, disturbance classes were evident as tabulated while disturbance classes were altered in plots subjected to site preparation. Soil strength estimates were made by manually inserting a Rimik CP20 recording cone penetrometer to a depth of 0.50 m and recording resistance in 0.025 m increments in accordance with American Society of Agricultural Engineers standards (ASAE, 2000). A total of six insertions were recorded for each plot location and a mean of each insertion calculated for 0.025 m depth increment. Volumetric water content was estimated by time domain reflectometry (TDR) (Topp et al., 1982) and calculated for three depth increments: 0.0–0.15, 0.15–0.30, and 0.30–0.45 m via metal rods of 0.15, 0.30 and 0.45 m lengths (Table 1). Penetrometer insertions and TDR readings were conducted in close proximity. Analysis of variance (ANOVA) and separation of means by Duncan's Multiple Range Tests were conducted to determine significance using the Statistical Analysis System (SAS Institute, 2001).

## 3. Results

### 3.1. Site disturbance

The degree of disturbance that occurred in response to harvesting under two soil moisture conditions was less pronounced in dry harvested sites than wet harvested sites (Table 2). Surface conditions in dry harvested sites remained relatively undisturbed with disturbances limited to less than 14% of the area within the harvested blocks. In contrast, surface disturbance in wet harvested sites included all disturbance classes and impacted between 50 and 91% of the blocks harvested. It was expected that a greater degree of disturbance would occur on the wet harvested sites but more surface disturbance might have been expected in the dry harvest areas due to the hydric nature of wet pine flats throughout the year.

Table 1
Soil moisture content (%) (v/v) of select soil depths in a wet pine flat subjected to harvesting under two soil moisture regimes and three methods of site preparation, South Carolina

| Treatment[a] | Soil depth (m) | Volumetric water content (%) |
|---|---|---|
| WFP | 0.00–0.15 | 47.3 |
| | 0.15–0.30 | 39.9 |
| | 0.30–0.45 | 45.3 |
| DFP | 0.00–0.15 | 43.9 |
| | 0.15–0.30 | 40.3 |
| | 0.30–0.45 | 42.2 |
| WB | 0.00–0.15 | 33.4 |
| | 0.15–0.30 | 35.9 |
| | 0.30–0.45 | 45.0 |
| DB | 0.00–0.15 | 27.3 |
| | 0.15–0.30 | 39.2 |
| | 0.30–0.45 | 42.4 |
| WMB | 0.00–0.15 | 32.5 |
| | 0.15–0.30 | 34.6 |
| | 0.30–0.45 | 33.7 |
| CON | 0.00–0.15 | 36.0 |
| | 0.15–0.30 | 35.6 |
| | 0.30–0.45 | 43.6 |

[a] Treatments definitions: WFP, wet harvest, no site preparation; DFP, dry harvest, no site preparation; WB, wet harvest, bedded; DB, dry harvest, bedded; WMB, wet harvest, mole plowed and bedded.

### 3.2. Soil strength

Soil strength increased with depth regardless of soil moisture condition at the time of harvest (WFP and DFP) and generally exceeded CI values of non-harvested sites (CON) in the soil surface layer (0.0–0.15 m) and below 0.30 m (Fig. 2). Coefficients of variation (CV) associated with CI measurements of WFP, DFP and CON by depth are included in Table 3. Cone index values of CON exceeded WFP and DFP between 0.20 and 0.275 m and may be indicative of a man-made or naturally occurring hardpan. Hardpans by definition are compact subsoil layers that are impervious to air, water and root penetration as a result of cementation of soil particles, poor soil structure or compaction of soil layers by machine trafficking (Hillel, 1982). Harvest operations appeared to reduce soil strength of the hardpan layer especially under high soil moisture conditions. A comparison of soil strength values

Table 2
Percentage (%) of soil disturbance classes within a wet pine flat logged under two soil moisture regimes, South Carolina

| Block | Disturbance class[a] | Treatments[b] | | | | |
|---|---|---|---|---|---|---|
| | | WMB | WFP | WB | DFP | DB |
| 1 | UNT | 43.8 | 20.0 | 48.8 | 90.0 | 86.2 |
| | COMP | 18.8 | 28.8 | 12.5 | 10.0 | 13.9 |
| | RUT1 | 25.0 | 26.3 | 18.8 | | |
| | RUT2 | 10.0 | 23.8 | 20.0 | | |
| | PUD | 2.5 | 1.3 | 0.0 | | |
| 2 | UNT | 23.9 | 9.1 | 22.2 | 98.7 | 93.5 |
| | COMP | 21.6 | 20.8 | 25.9 | 1.3 | 6.5 |
| | RUT1 | 22.7 | 50.7 | 45.7 | | |
| | RUT2 | 29.6 | 19.5 | 6.2 | | |
| | PUD | 2.3 | 0.0 | 0.0 | | |
| 3 | UNT | 18.8 | 9.3 | 12.5 | 95.0 | 88.0 |
| | COMP | 16.3 | 28.0 | 22.5 | 5.0 | 12.0 |
| | RUT1 | 47.5 | 26.7 | 15.0 | | |
| | RUT2 | 17.5 | 25.3 | 27.5 | | |
| | PUD | 0.0 | 10.7 | 22.5 | | |

Source: Preston (1996).
[a] Disturbance classes: UNT, untrafficked; COMP, compressed soil; RUT1, ruts <0.2 m; RUT2, ruts >0.2 m; PUD, churned/puddled soils.
[b] Treatments: WMB, wet harvest, mole plowed, bedded; WFP, wet harvest, flat planted; WB, wet harvest, bedded; DFP, dry harvest, flat planted; DB, dry harvest, bedded.

Table 3
Coefficients of variation (CV) (%) of cone index measurements in harvested and bedded treatments of a wet pine flat, South Carolina

| Soil depth (cm) | Treatment[a] | | | | | |
|---|---|---|---|---|---|---|
| | WFP | DFP | WMB | WB | DB | CON |
| 0.0–2.5 | 40.0 | 85.3 | 34.3 | 45.5 | 51.5 | 34.4 |
| 2.5–5.0 | 42.3 | 89.0 | 36.4 | 58.8 | 40.0 | 42.9 |
| 5.0–7.5 | 36.2 | 90.8 | 31.3 | 51.6 | 35.1 | 36.2 |
| 7.5–10.0 | 32.8 | 80.6 | 24.2 | 61.1 | 35.4 | 28.6 |
| 10.0–12.5 | 31.0 | 79.6 | 29.0 | 60.0 | 34.2 | 30.2 |
| 12.5–15.0 | 37.2 | 71.4 | 22.0 | 67.4 | 31.7 | 39.0 |
| 15.0–17.5 | 41.9 | 70.1 | 26.1 | 59.2 | 31.1 | 49.5 |
| 17.5–20.0 | 44.1 | 64.3 | 30.0 | 78.3 | 26.1 | 50.5 |
| 20.0–22.5 | 53.9 | 64.0 | 34.6 | 68.7 | 23.1 | 52.5 |
| 22.5–25.0 | 40.0 | 57.4 | 36.5 | 36.4 | 26.4 | 50.4 |
| 25.0–27.5 | 33.6 | 56.5 | 38.7 | 43.4 | 31.8 | 43.0 |
| 27.5–30.0 | 38.3 | 50.7 | 38.8 | 40.5 | 33.3 | 30.8 |
| 30.0–32.5 | 40.2 | 51.5 | 36.5 | 42.7 | 28.8 | 26.1 |
| 32.5–35.0 | 34.2 | 36.6 | 38.7 | 45.1 | 25.3 | 21.1 |
| 35.0–37.5 | 37.1 | 39.6 | 38.3 | 45.0 | 25.6 | 20.2 |
| 37.5–40.0 | 26.1 | 25.5 | 36.9 | 37.0 | 26.6 | 19.0 |
| 40.0–42.5 | 30.1 | 29.4 | 36.5 | 36.9 | 20.4 | 20.7 |
| 42.5–45.0 | 25.2 | 22.6 | 33.6 | 40.4 | 22.6 | 22.5 |
| 45.0–47.5 | 23.2 | 27.1 | 33.8 | 32.9 | 20.2 | 25.4 |
| 47.5–50.0 | 25.2 | 23.7 | 33.6 | 28.0 | 18.2 | 25.0 |

[a] Treatments: WFP, wet harvest, flat planted; DFP, dry harvest, flat planted; WMB, wet harvest, mole plowed, bedded; WB, wet harvest, bedded; DB, dry harvest, bedded.

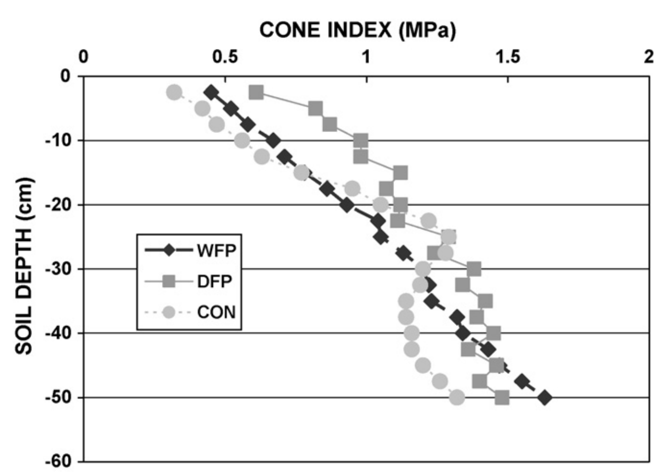


Fig. 2. Comparison of cone index levels in a wet pine flat subjected to harvesting under two soil moisture conditions: wet and dry and compared with a non-harvested reference plot, South Carolina.

Table 4
Significance of factors influencing soil strength in a wet pine flat subjected to harvesting or site preparation, South Carolina

| Source of variation | d.f.[a] | $F$ value | Pr > $F$ |
|---|---|---|---|
| Harvested | | | |
| Treatment (TRT) | 2 | 0.81 | 0.51 |
| Depth (DPTH) | 19 | 36.46 | 0.001 |
| Interaction (TRT × DPTH) | 38 | 1.27 | 0.17 |
| Bedded | | | |
| Treatment (TRT) | 2 | 1.15 | 0.40 |
| Depth (DPTH) | 19 | 211.46 | 0.001 |
| Interaction (TRT × DPTH) | 38 | 2.76 | 0.001 |

[a] d.f.: degrees of freedom.

of harvested treatments indicated CI values of DFP exceeded WFP to a depth of 0.40 m below which the CI of WFP exceeded DFP. An ANOVA indicated depth (DPTH) ($P < 0.001$) to have a highly significant effect on soil strength while no significance was detected for treatment (TRT) ($P = 0.51$) or the interaction of treatment × depth (TRT × DPTH) ($P = 0.17$) (Table 4). Preharvest influence on soil strength was not significant ($P = 0.40$) as indicated in a covariate analysis using preharvest (CON) soil strength as a covariate. Coefficients of variation associated with harvested sites indicated a higher degree of variability in dry harvest sites than wet harvested sites (Table 3).

Bedding of harvested sites reduced soil strength under both soil moisture conditions resulting in lowered penetration resistance in comparison with the corresponding harvested condition (Fig. 3). Penetration resistance was less than 1.0 MPa to approximately 0.35 m in WMB and WB and to approximately 0.40 m in DB compared to WFP (0.20 m) and DFP (0.10 m), respectively. Penetration resistance was similar among all bedded treatments (less than 0.50 MPa) to a depth of 0.20 m but diverged as indicated by elevated CI values of WMB and WB that exceeded DB at comparable depths. A maximum resistance of 1.4 MPa was measured at the lowest sampled depth of 0.50 m among bedded treatments (WMB). An ANOVA indicated the main effect of TRT ($P = 0.40$) did not

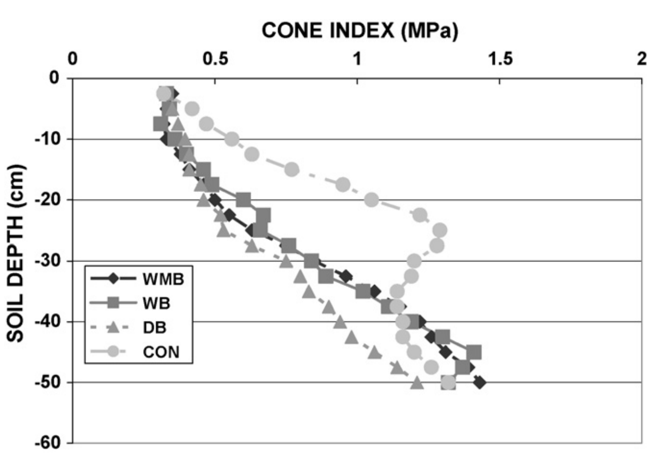


Fig. 3. Comparison of cone index levels in a wet pine flat subjected to harvesting under two soil moisture conditions and subjected to two methods of site preparation, South Carolina.

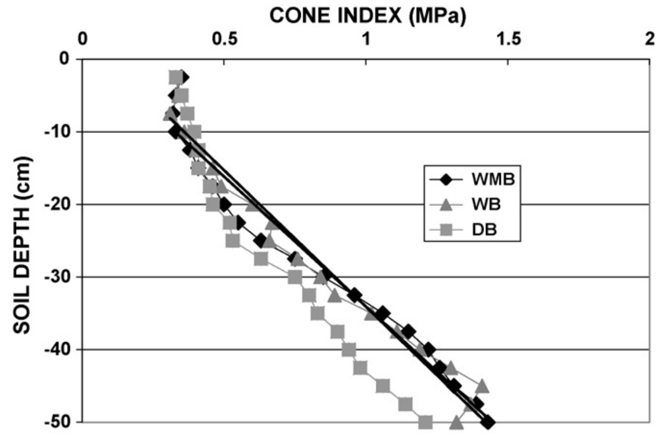


Fig. 4. A comparison of regression lines of cone index versus depth in a wet pine flat harvested under two soil moisture conditions and two methods of site preparation, South Carolina.

have a significant impact on soil strength in bedded treatments while DPTH ($P < 0.001$) and the interaction of TRT × DPTH ($P < 0.001$) were significant (Table 4). The interaction of TRT × DPTH was analyzed by computing regression parameters by simple linear regression analysis of soil strength changes by depth for each treatment and comparing the slope parameter in an ANOVA for significant differences among the bedded treatments. The results indicated soil strength of DB was significantly different from WMB and WB (Fig. 4). The regression equations and $r^2$ values for bedded treatments are included in Table 5.

Soil strength levels as a result of harvesting varied as indicated by the CI values associated with each disturbance class of WFP and DFP (Fig. 5). In WFP, untrafficked (UNT) and churned/puddle sites (PUD) exhibited the highest mechanical resistance in the upper 0.1 m. This was not expected due to the undisturbed condition of UNT sites and higher degree of soil water saturation of PUD sites. Soil strength in compressed (COMP) and shallow rutted (RUT1) locations were less than 0.5 MPa but exceeded other disturbance classes below 0.15 m with the exception of UNT sites below 0.35 m. Deeply rutted sites (RUT2) exhibited the lowest soil strength among disturbance classes at all comparable depths of WFP. Below 0.20 m less disturbance in soil surface layers as indicated by the presence of compressed or shallow rutted disturbances resulted

Table 5
Regression equations and coefficients for soil strength versus depth in bedded treatments and soil strength versus depth for select disturbance classes in a wet pine flat harvested under high soil moisture conditions

| | Regression equation | $r^2$ |
|---|---|---|
| Wet vs. dry bedded condition | | |
| WMB | CI = 17.42–357.84DPTH | 0.95 |
| WB | CI = 30.06–374.95DPTH | 0.96 |
| DB | CI = 74.18–499.82DPTH | 0.95 |
| Disturbance classes | | |
| UNT: untrafficked | CI = −4.71–271.19DPTH | 0.95 |
| RUT2: ruts >0.2 m | CI = 72.22–436.49DPTH | 0.95 |
| PUD: churned/puddled | CI = 166.95–497.94DPTH | 0.97 |

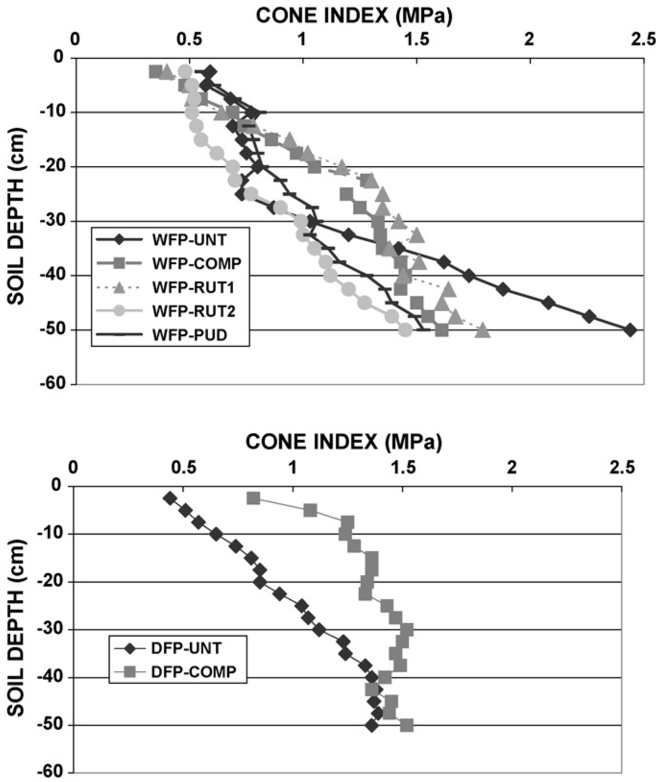


Fig. 5. Soil strength levels in soil disturbance classes in a wet pine flat subjected to harvesting under two levels of soil moisture and no site preparation, South Carolina.

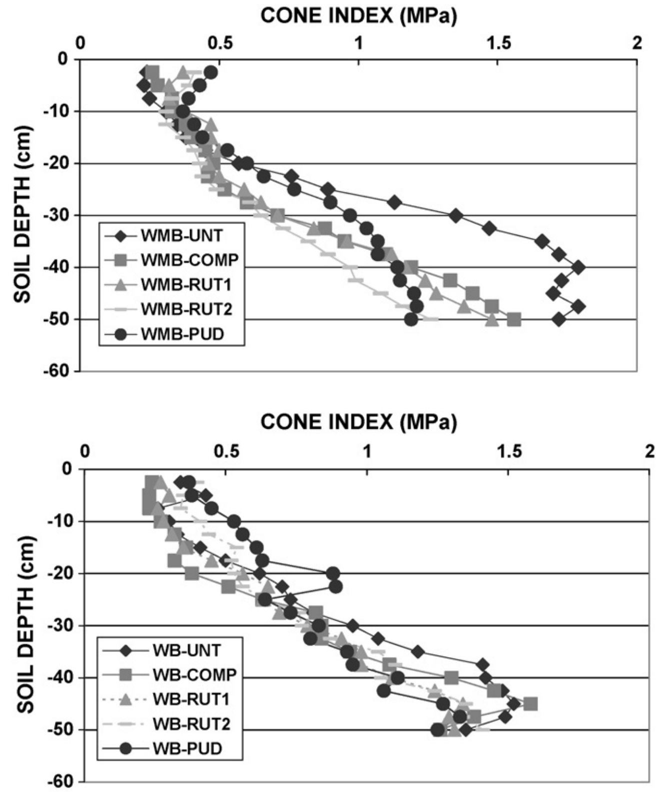


Fig. 6. Soil strength levels of disturbance classes in a wet pine flat harvested under elevated soil moisture conditions and subjected to two methods of site preparation.

in higher soil strength with depth while highly disturbed classes (RUT2 and PUD) exhibited lower penetration resistance. The highest CI values were attained in the lowest depth of each disturbance class and ranged between 1.3 and 2.5 MPa. Penetration resistance increased with depth in DFP regardless of disturbance level and CI values of COMP exceeded UNT (Fig. 5).

Site preparation lowered soil strength to less than 0.50 MPa in all disturbance classes in the upper 0.20 m of WMB and for areas that were less disturbed (UNT, COMP, and RUT1) in WB (Fig. 6). Below 0.20 m in WMB, highly disturbed classes (RUT2 and PUD) attained a maximum soil strength of approximately 1.25 MPa compared to penetration resistance levels of 1.5–1.75 MPa in less disturbed areas (UNT, COMP, and RUT1). Cone index values of UNT sites in WMB exhibited higher penetration resistance below 0.20 m compared with all other disturbance classes and attained the greatest maximum soil strength. Differences in soil strength were apparent in the upper 0.20 m of WB with CI values elevated in highly disturbed classes, especially PUD. This trend diminished below 0.20 m where all disturbance classes increased similarly with depth and maximum soil strength levels of approximately 1.5 MPa achieved in UNT and COMP sites compared to 1.25 MPa in areas with higher disturbance levels.

Soil strength of UNT and COMP areas of DB was less than 1.0 MPa to a depth of 0.40 m and the highest soil strength levels of approximately 1.25 MPa attained at the lowest depth evaluated (Fig. 7). Coefficients of variability were slightly higher in WB in the upper 0.25 m compared with WMB and DB and may be an indication of differences in soil moisture or compaction levels that resulted from bedding; CVs in WMB and DB were fairly consistent with depth (Table 3).

An evaluation of the significance of disturbance class on soil strength was examined as a split plot in the original randomized block design in which each harvest condition (wet versus dry) was analyzed separately (Table 6). An ANOVA of wet harvested treatments indicated TRT ($P < 0.10$), DPTH ($P < 0.001$), and disturbance class

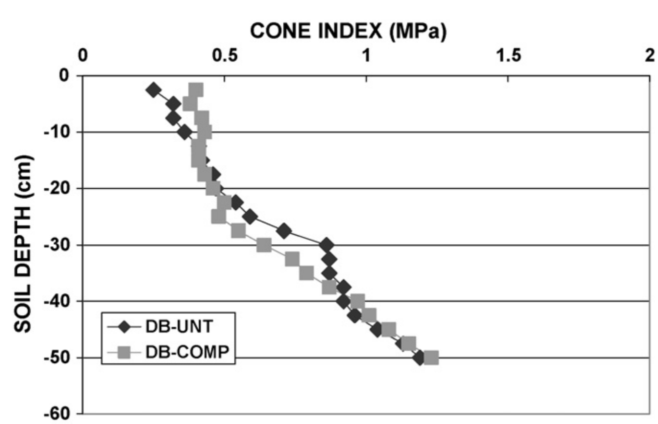


Fig. 7. Soil strength levels in a wet pine flat harvested under low soil moisture conditions and subjected to site preparation, South Carolina.

Table 6
Significance of factors affecting soil strength in a wet pine flat subjected to harvesting under two soil moisture conditions, South Carolina

| Source of variation | d.f. | $F$ value | Pr > $F$ |
|---|---|---|---|
| Wet harvest: single factors | | | |
| Treatment (TRT) | 2 | 6.20 | 0.06 |
| Depth (DPTH) | 19 | 186.16 | 0.001 |
| Disturbance class (DISTCL) | 4 | 3.50 | 0.02 |
| Wet harvest: interactions | | | |
| TRT × DPTH | 38 | 1.06 | 0.38 |
| TRT × DISTCL | 8 | 1.09 | 0.41 |
| DISTCL × DPTH | 76 | 2.56 | 0.001 |
| Dry harvest: single factors | | | |
| TRT | 1 | 31.85 | 0.03 |
| DPTH | 19 | 16.34 | 0.0001 |
| DISTCL | 1 | 2.69 | 0.18 |
| Dry harvest: interactions | | | |
| TRT × DPTH | 19 | 1.47 | 0.11 |
| TRT × DISTCL | 1 | 3.15 | 0.15 |
| DISTCL × DPTH | 19 | 1.10 | 0.35 |

(DISTCL) ($P < 0.05$) to have a significant impact on soil strength. The interactions of treatment × disturbance class (TRT × DISTCL) ($P = 0.41$) and TRT × DPTH ($P = 0.35$) were not significant for soil strength but disturbance class × depth (DISTCL × DPTH) was significant ($P < 0.001$). Significant differences would be expected by treatment due to the type of comparison: bedded versus flat planted sites as well as increased soil strength with depth. Disturbance class influenced soil strength with differences detected between UNT and RUT2 and PUD sites**.** A least squares regression computed regression parameters for changes in soil strength for the interaction of disturbance class × depth ($P < 0.1$) (Table 5) and indicated UNT to be significantly different compared to RUT2 and PUD classes (Fig. 8). A similar ANOVA procedure conducted on dry treatments indicated TRT ($P < 0.05$) and DPTH ($P < 0.0001$) to have a significant impact on soil strength (Table 6).

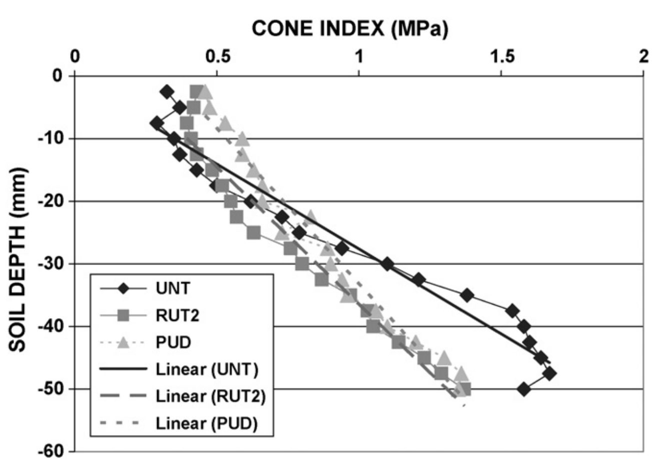


Fig. 8. Regression lines of cone index versus depth of select soil disturbance classes in a wet pine flat harvested under high soil moisture conditions, South Carolina.

## 4. Discussion

Surface disturbances occurred extensively on wet harvested sites as indicated by the percentage of surface disturbances (>50%) in response to harvesting and the number of disturbance classes tabulated on wet sites. Soil disturbances characterized as rutted and/or puddle/churned likely resulted from trafficking at saturation when soil strength is reduced and soil aggregation is destroyed (Greacen and Sands, 1980; Sharma and deDatta, 1985; McDonald et al., 1995). The results of this study reflected results previously reported in which elevated soil moisture content was critical in the formation of surface disturbances on harvested Coastal Plain soils of Georgia and Mississippi (Karr et al., 1987; Burger et al., 1989; Aust et al., 1993).

Soil strength increased in this study in surface and subsurface soil layers compared to the undisturbed (CON) condition, the impact due to machine trafficking and attenuated by soil moisture status. Mean soil strength of harvested soil surface layers under both soil moisture regimes measured less than 0.75 MPa and exceeded CON in the surface layers. Soil moisture levels near field capacity at the time of harvest can result in compacted layers due to a denser packing of soil particles and/or aggregates (Akram and Kemper, 1979). Murosky and Hassan (1991) reported alteration of soil strength in the surface layer of a poorly drained soil in Mississippi in which soil strength levels of 2.0 and 3.0 MPa were recorded under moisture contents of 0.55 and 0.42 g $g^{-1}$, respectively. Differences in soil strength would be expected under the conditions of this study as soil moisture content significantly influences soil strength when soil is subjected to compactive forces (Ayers and Perumpral, 1982). Peak soil strength of a soil occurs at a specific soil moisture content during compaction and has been previously reported to occur at field capacity. The soil moisture content measured at the time of harvest may have corresponded more closely to field capacity and resulted in higher soil strength. Differences in soil strength between wet and dry harvest treatments were not statistically significant in this study and the levels were below cone index levels considered to be root limiting.

Improvements in soil strength occurred during site preparation of both wet and dry harvested treatments. Physical disruption of the soil profile during tillage is a common practice in agricultural systems to lower soil strength and improve aeration and water management (Eck and Unger, 1985; Hammel et al., 1985). Bedding lowered soil strength in the upper portion of the bedding profile regardless of soil moisture content. Soil strength was observed to increase within beds and attained a maximum level at the lowest sampled depth in each treatment although DB exhibited consistently lower soil strengths than WMB and WB in the soil profile. Lack of uniformity in soil strength with depth in beds may be due to incorporation of denser subsoil material into the beds which significantly increased soil strength with depth. A similar trend was reported for soils of the lower and upper Coastal Plain that had been harvested and bedded in which bulk density at the base of each bed was elevated to levels which matched the soil surface on which the beds were formed (Gent et al., 1983, 1986). Lower soil strength in DB was not expected but may be the result of elevated soil moisture content at the time of bedding. A covariate analysis with volumetric water content as the covariate indicated VWC did not influence soil strength within the limits of this study and soil moisture levels were sufficiently elevated to assess differences among treatments. Soil strength determination at a standard water potential is recommended to ensure differences are due to treatment and not soil water content (O'Sullivan et al., 1987; Henderson et al., 1988). Mole plowing prior to bedding did not appear to have an impact on soil strength as the cone index values of WMB and WB were not significantly different from each other. The impact of mole plowing may be limited to subsoil layers below the bedded surface and not detectable or significant in this study.

Disturbance classes significantly influenced soil strength among wet harvested treatments, underscoring the impact of harvest conditions on surface disturbances in wet pine flats. Mean soil strength decreased as disturbance intensity increased but significant differences were detected only between the least disturbed (UNT) and deeply rutted (RUT2) or churned/puddled (PUD) locations. Variability in soil moisture content within wet harvested blocks undoubtedly contributed to the formation of each disturbance class and its subsequent mechanical resistance. Burger et al. (1989) noted that differences in surface disturbance patterns on a wet pine flat were related to soil moisture content with rutted/churned and slightly disturbed associated with 30 and 18% soil moisture content, respectively. It was determined that preharvest soil strength made a significant contribution to disturbance class formation in wet harvested sites with higher soil moisture contents associated with more highly disturbed areas. Less disturbed classes in WFP were presumably associated with areas of low soil moisture status that resulted in lower disturbance on a visual basis but increased in soil strength.

Soil strength characteristics for each disturbance class in bedded sites resembled trends previously presented, namely, decreased soil resistance in the upper profile followed by increased soil strength with depth. Mole plowing (WMB) prior to bedding appeared to have its greatest impact on untrafficked sites as its soil strength exceeded all disturbance classes in WMB and the untrafficked class in WB. The impact of mole plowing may be additive by further lowering soil moisture content from the existing soil moisture status. This would result in drier soils and higher soil strength would be expected to occur due to the relationship between soil strength and soil moisture content. The same mechanism may not be applicable to higher soil moisture contents of more highly disturbed locations. Soil strength of each disturbance class was fairly uniform in its distribution with depth in WB and DB.

Bedding has proven to be effective in ensuring survival and productive growth of loblolly pine on wet pine flats, especially on poorly drained sites (Hatchell, 1981; McKee and Wilhite, 1986; Allen et al., 1990). Pine productivity as total green weight biomass by age five was adequate on the sites under consideration in this paper regardless of whether harvesting occurred when wet or dry (Eisenbies et al., 2004).

## 5. Conclusion

Harvesting in a wet pine flat in the Coastal Plain of South Carolina produced a high degree of surface disturbance when soil moisture condition was elevated compared to drier site conditions. Ruts greater than 0.2 m in depth and puddling of soils were evident when soil moisture was elevated. Bedding lowered soil strength in the upper portion of the bedding profile regardless of soil moisture content but tended to increase with depth. This was assumed to occur as a result of placing loose soil material over denser, more compacted soil layers. Mole plowing did not appear to influence the final penetration resistance in this study. It appeared that areas of the wet harvest treatments that exhibited a combination of low soil strength and elevated soil moisture were associated with higher degrees of disturbance. A more in-depth examination of the relationship among soil moisture, soil strength and machine trafficking would be necessary to understand more fully the site conditions that contribute to higher degrees of soil disturbance and their influence on pine productivity.

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