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Soil Physical Disturbance and Logging Residue Effects on Changes in Soil Productivity in Five-Year-Old Pine Plantations

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ABSTRACT

There has been much concern that traffic associated with the harvesting of intensively managed pine plantations reduces long-term soil-site productivity. Trafficking, especially during wet periods, can cause severe soil physical disturbance and redistribution of woody residues. Although the negative effects of soil compaction and rutting on root growth and the importance of organic matter for maintaining site productivity are well known, the connection between these factors and actual changes in soil and site productivity has been difficult to evaluate. Three productive, 20-ha loblolly pine (*Pinus taeda* L.) plantations located on fertile "wet pine flats" on the coastal plain of South Carolina were subjected to wet- and dry-weather harvesting and mechanical site preparation. A factorial design was used to evaluate changes in soil-site quality after 5 yr based on postharvest classifications of soil physical disturbance, harvest residue removal, and the type of site preparation using a recently developed rank diagnostic approach. Trees on disturbed sites performed as well or better than trees on minimally disturbed sites with average levels of harvest residues. Bedding restored relative soil-site productivity (based on the rank diagnostic) on all but heavily disturbed sites with >25% bare soil; however, these heavily disturbed sites comprised about 5% of the total area harvested. Moderate levels of disturbance may increase relative soil-site productivity, perhaps by controlling competition or increasing nitrogen mineralization rates. Sites such as these may be good alternatives to more sensitive sites for wet-weather harvesting.

SOUTHERN PINE PLANTATIONS are among the most intensively managed forests in the United States (Allen and Campbell, 1988; Conner and Hartsell, 2002). A total of 89 million hectares on the Southeastern Coastal Plain and Piedmont extending from East Texas to Virginia are forested, and nearly 20 million hectares are used for the production of commercial species of southern yellow pine (Conner and Hartsell, 2002). Production of southern yellow pine plantations can range from 10 m^3 ha^{-1} yr^{-1} to as high as 28 m^3 ha^{-1} yr^{-1} of wood fiber (Borders and Bailey, 2001). Two thirds of softwood timber harvests are expected to come from plantation forests by 2050 (USDA Forest Service, 2001).

There has been a great deal of scientific and societal concern in the past several decades that the trafficking associated with intensive forest harvesting and management, especially associated with skid trails, reduces seedling survival and reduces the height and diameter growth of young trees (Moehring and Rawls, 1970; Hatchell et al., 1970; Lockaby and Vidrine, 1984; Tiarks, 1990; Miwa et al., 2004). Most of the literature has attributed soil productivity decline to erosion, compaction and rutting, and loss or removal of soil organic matter (Gent et al., 1983; Powers et al., 1990; Worrell and Hampson, 1997; Kozlowski, 1999). However, the implication of the body of research remains unclear, and most current forest practices need further evaluation and research on a variety of sites (Miller et al., 2004).

Miwa et al. (2004) and Miller et al. (2004) provide excellent reviews of the effects of soil and site disturbance on forest productivity for pine plantations in the southeastern USA. Assessing the effects of disturbance on long-term productivity is challenging because trees are very adaptive and reside on sites for a long period of time (Miller et al., 2004). In general, there have been mixed results with regard to the effects harvesting disturbances and site preparation have on site productivity in the Southeast, but they seem to be very site specific (Miwa et al., 2004). Aust et al. (1995) showed that not all sites respond to disturbance the same, and the case has been made that forest management must be tailored to specific forest types and management regimes (Richardson et al., 1999; Fox, 2000).

In response to trafficking concerns, many states, such as South Carolina, incorporate harvesting best management practices (BMPs) as a means of protecting site quality by limiting rutting and compaction, especially during wet weather harvesting, for the expressed purpose of protecting long-term productivity (Aust and Blinn, 2004). According to Darrel Jones, Coordinator of BMP Inspectors (personal communication, 2002), South Carolina Forestry Commission inspectors look for harvesting sites with deep rutting (>30 cm) over 20% of the site.

Although ample studies exist that show that forest practices can negatively affect important soil physical and chemical properties that affect tree growth, the direct link between disturbance and actual productivity declines remains elusive (Morris and Miller, 1994; Burger, 1996; Worrell and Hampson, 1997). Considering that the exact potential productivity of a site is impossible or exceedingly difficult to determine and that myriad biotic and abiotic factors that can influence site productivity, most scientific studies are at a disadvantage with regards to establishing this link (Powers et al., 1990; Morris and Miller, 1994). Furthermore, comparing forest productivity between rotations is particularly challenging when

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Abbreviations: ANCOVA, analysis of covariance; BMPs, best management practices; dbh, diameter breast height; HRI, harvest residue index; NPP, net primary productivity; PDI, physical disturbance index; RCSB, rank change based on stand biomass; RCSI, rank change based on site index.

trying to isolate changes in soil-site productivity due to management effects (Morris and Miller, 1994; Burger, 1996; Vance, 2000). The difficulties with direct comparisons of net primary productivity (NPP), volume, biomass, or site index between rotations are caused by changes of climate (Boardman, 1978; Shoulders and Tiarks, 1980; Kirschbaum, 2000), intensive silviculture (Terry and Hughes, 1975; Hasenauer et al., 1994), the use of genetically improved trees (Schultz, 1997; Stanturf et al., 2003), physiography, and drainage class (Terry and Hughes, 1975; Carmean et al., 1989). Even the specific productivity model selected (Carmean, 1975) renders direct comparisons between two growth distributions (e.g., NPP, volume, biomass, or site index) inappropriate for evaluating changes in soil-site productivity. Computer modeling has been used to adjust for these factors, but these modeling efforts are not always ideal, and scaling problems often arise (Proe et al., 1994). Therefore, the development of methodologies that allow field evaluations of treatment and disturbance effects on actual changes in soil-site quality and production would be a significant improvement (Comerford et al., 1994).

The ultimate goal of sustainable forestry, in the context of intensive silviculture, should be to ensure that management activities do not exceed the capacity of the forest to resist or recover via natural processes or facilitated by artificial means (Switzer, 1978; Nambiar, 1996; Worrell and Hampson, 1997; Miller et al., 2004). Certain sites may prove resistant to disturbance, and some sites may recover naturally from disturbance (Aust et al., 1997; Maul et al., 1999; Kelting et al., 1999). In this regard, the actual efficacy, efficiency, or even necessity of some BMPs as a way to preserve long-term site productivity has not been fully substantiated because of site-specific management requirements (Reisinger et al., 1988; Aust and Blinn, 2004). Given that costs of BMP implementation can be very high (Shaffer et al., 1998; Cubbage, 2004), ensuring that BMPs are effective should be a prime objective.

The objectives of this article are (1) to evaluate the effect of soil physical disturbance and harvesting residues on changes in site-soil productivity and the ability of bedding to remediate productivity and (2) to describe the prevalence and determine the specific cause of disturbance combinations that do not respond to bedding.

MATERIALS AND METHODS

The study site is located in Colleton County, South Carolina, on the Atlantic Coastal Plain approximately 100 km west of Charleston. The topography is flat to gently rolling marine terraces. Soil parent material consists of marine and fluvial sediments deposited during the Oligocene and Pleistocene eras, which feature the phosphatic Cooper Marl (Ellerbe and Smith, 1966; Stuck, 1982). All soils are poorly to somewhat poorly drained and have aquic moisture regimes (Soil Survey Staff, 2003). These sites are classified by the Cowardin system as Palustrine, forested, needle-leaved evergreen wetlands (Cowardin et al., 1979) and are commonly referred to as "wet pine flats" (Messina and Conner, 1998). Regionally, these sites are typically managed as loblolly pine (*Pinus taeda* L.) plantations and are considered among the most productive in the Southeast.

In 1992, three 20-ha, bedded, loblolly pine plantations, located approximately 2.5 km apart, were selected based on similar age (20–25 yr), soil, and hydrologic conditions. Several soil units were represented on these sites and included one Alfisol, one Mollisol, and two Ultisols as mapped by the Natural Resource Conservation Service (Stuck, 1982). The soils are similar enough that the present landowners group these sites as a single soil-mapping unit. Surface drainage is largely controlled by microtopography and subsurface drainage by thick argillic horizons of low permeability that cause perched water tables (Xu et al., 2002).

A range of soil physical and harvesting residue disturbances were induced by conducting harvests on five independent, "operational-scale" plots within the block; two were conducted in dry weather and three in wet weather. Three types of site preparation followed the harvesting treatments: one conventional (bedding), one experimental (mole-plowing), and flat planting (no site preparation). Due to the equivalent growth and hydrologic responses between the bedded and mole plowed sites (wet harvested only), we pooled these two operations for the purposes of this experiment to ensure that all disturbance types were fully represented among the wet harvested plots (Xu et al., 2002; Eisenbies et al., 2004). A sixth plot in each block consisted of a no-harvest control and was not used in this experiment. Disturbances were applied in this manner to ensure that the degree and distribution of soil physical and harvesting residue disturbances would be operationally realistic.

Harvesting was performed by conventional commercial logging operations using mechanized fellers (Hydro-Axe, Model 411; Blount Inc., Owatonna, MN, and Model 105; Franklin Treefarmer, Franklin, VA) and wide-tired (81.3 cm) buncher/grapple skidders (Franklin, Model 170; Model 518; Caterpillar Inc., Peoria, IL, and Model 450C; Timberjack Group, Helsinki, Finland). Tire inflation ranged from 0.21 to 0.24 MPa. The treatment areas were laid out as individual harvest units with separate decks and skid trails. In the fall of 1993, two plots on each block received a dry-weather harvesting treatment.

In the spring of 1994, the remaining three plots on each block were harvested during wet conditions to maximize soil disturbance. Bedded sites were sheared and drum chopped by a Caterpillar D-8 tractor with V-blade and drum chopper before bed installation. Chemical weed control in the form of Imazapyr (1.2 L ha^{-1}) and Glyphosate (5.6 L ha^{-1}) was applied to each harvested unit in July 1995. Mole plowing was done in October 1995, and bedding was done in November 1995 using a mole-shank and modified bedding plow behind a D-8 tractor. The sites were hand planted in February 1996 with best first generation, open-pollinated family, loblolly pine seedlings provided by the MeadWestvaco Corp. nursery. As a precaution, nonbedded stands were double planted to emphasize treatment effects on productivity over that of stocking and survival effects. Extra seedlings were culled from double plantings that remained after the first year of growth (survival was excellent rendering that double planting effort unnecessary).

Data Collection

Before harvest, each 3.3-ha treatment area was overlain with a 20 × 20 m grid. Within each 20 × 20 m cell, a circular 0.008-ha measurement subplot was permanently established. A total of 1170 subplots were installed, and all subsequent stand measurements were collected at these "polypedon scale" subplots. Height and diameter (dbh) of all trees within the 0.008-ha subplots were measured before treatment installation. A second inventory of height and diameter (dbh) was conducted at age 5 in the second rotation at the same 0.008-ha subplots across the study.

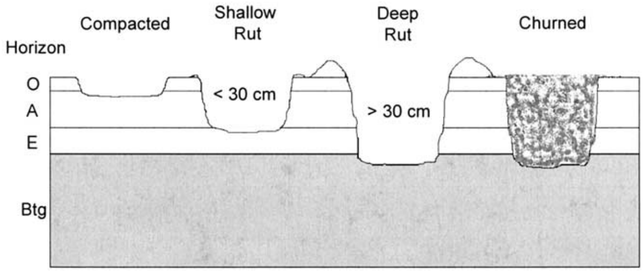

Fig. 1. Diagram illustrating soil physical disturbance classes after harvesting a poorly drained soil on a wet pine flat.

Soil physical and harvesting residue disturbance was evaluated immediately after harvest. Site disturbances associated with logging were characterized for the 20-m grid by visually determining the percent coverage of five types of physical disturbance (undisturbed, compressed, shallow rutting [<30 cm deep], deep rutting [>30 cm deep], and churning) using the procedure of Terry and Chilingar (1955) (Fig. 1) and five levels of harvesting residue (bare soil exposed by logging, litter, light slash [<2.5 cm diameter], heavy slash [>2.5 cm diameter], and slash piles >30 cm deep) (Fig. 2). Single levels of physical disturbance or harvesting residues are rarely expressed at the polypedon scale but instead occur as a mosaic.

Two indexes were used to describe this mosaic. A physical disturbance index (PDI) was determined by calculating a weighted average based on percent coverage and an ordinal score for each level of increased disturbance: undisturbed (1), compacted (2), shallow rutted (3), deep rutted (4), and churned (5). A harvest residue index (HRI) was similarly calculated for woody debris and litter. The ordinal scores were based on decreasing amounts of harvesting residue: piles (1), heavy slash (>2.5 cm diameter) (2), light slash (<2.5 cm diameter) (3), litter only (4), and bare soil (5). Although ordinal scores assume a uniform interval of effect, they are commonly used when there is no basis for assigning other scores (Schabenberger and Pierce, 2002). The purpose of the two indexes is to provide a systematic means for differentiating between various levels of visually determined disturbance that is comparable with the determinations used by state BMP inspectors.

The soil physical disturbance of each 20-m grid cell was separated into three categories: "minimal" disturbance if the PDI equaled 1, "moderate" disturbance if the PDI was between 1 and 2.5, and "heavy" disturbance if the PDI was between 2.5 and 5. The pooling of the rutting and churning disturbances was based on the suggestion by Aust et al. (1998) that these physical disturbance types may be overdifferentiated with regard to certain soil properties (e.g., bulk density, soil moisture, and saturated hydraulic conductivity).

The harvesting residues of each 20-m grid cell were categorized as Class I if the residue index was 3.3 or less and there was <25% bare soil after harvesting, Class II if the residue index was >3.3 and there was <25% bare soil, and Class III if there was >25% bare soil regardless of the residue index. The total dry weight biomass of the residues in the 20-m cell was calculated using regressions that estimated biomass from the percent coverage of each of the five residue categories (Eisenbies et al., 2002).

Evaluating Changes in Soil-Site Productivity Using Rank

The biotic, abiotic, and cultural practices that influence forest productivity have been conceptualized many ways (Switzer, 1978; Burger, 1994; Morris and Miller, 1994). Morris and Miller (1994) described forest productivity as a function of plant

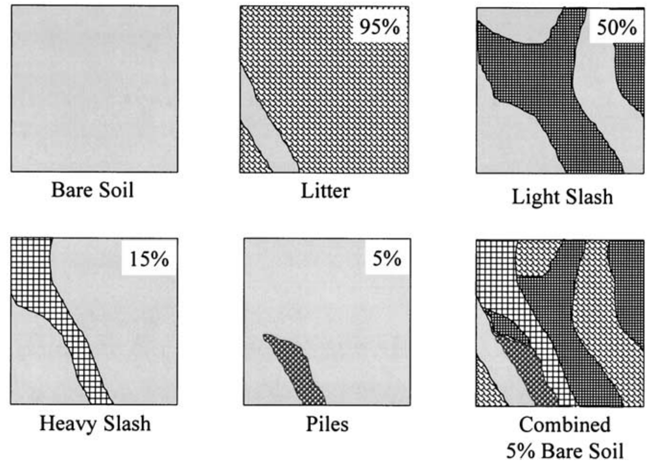

Fig. 2. Percentage of cover for each residue type was determined separately and combined to determine the harvesting residue disturbance category. This diagram illustrates how a 20 × 20 m subplot with litter (95%), light slash (50%), heavy slash (15%), and piles (5%) might be superimposed on bare ground and each other. This example would be defined as a Class II site using the decision factors described in the METHODS section.

potential, climate, soil-site quality, and catastrophe. This definition is useful because it separates soil-site quality from the major confounding factors that preclude productivity comparisons across rotations from being made. For the purpose of evaluating management impacts on site quality, we can focus on the soil-site component of the productivity model by further hypothesizing that changes in soil-site quality will be a function of silvicultural treatments, harvesting disturbance, and inherent site factors.

Distributions of NPP, volume, biomass, and site index are not consistent from rotation to rotation because of advances in crop genetics, silvicultural technology, climate, and the age at which measurements occur (Morris and Miller, 1994; Richardson et al., 1999). Production at the end of a second rotation can easily exceed the prior rotation due to technological improvements and may mask potential negative impacts caused by trafficking (Burger, 1994; Worrell and Hampson, 1997). Therefore, to evaluate the treatment effects on soil-site productivity change between rotations, we need to use a distribution that is independent of the confounding factors that limit our ability to make these comparisons.

The problems associated with using standard productivity measures can be partially controlled by making the assumption that regardless of a uniformly applied treatment, the rank of soil-site quality (as signified by site index or tree biomass) for a specific location remains relatively constant within a designated neighborhood at any point across time (i.e., the best sites are always the best, etc.). For the purpose of evaluating changes in productivity between rotations, the rank distribution is attractive because it is less affected by the confounding factors because it always has the same range and mean and has no outliers. Consequently, change in rank can be a meaningful diagnostic for relative changes in soil-site quality among treatments applied to a plot or forest site within a given neighborhood.

Data Analysis

Existing equations were used to calculate site indexes (base age 25) to three significant digits for each polypedon scale subplot (0.008-ha) at the end of the prior rotation and for the age-5 third quartile heights (Carmean et al., 1989). The

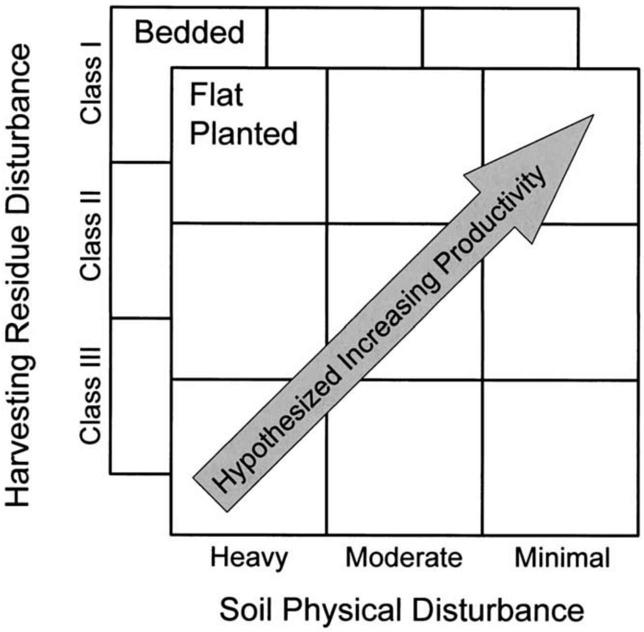

Fig. 3. Hypothetical response of productivity to levels of physical disturbance and amounts of harvesting residues for two levels of site preparation.

equations used were developed for loblolly pine in all but very poorly drained soils on the North Carolina and South Carolina coastal plain (Pienaar and Shiver, 1980). The third quartile height was used for the age-5 data because it was assumed that these trees would be the most likely to survive to represent the dominant or codominant trees at the end of the rotation. Existing equations were also used to calculate tree green weight biomass as a function of height and diameter for the end of the previous rotation (Bullock and Burkhart, 2003) and at age 5 for the new rotation (Phillips and McNab, 1982) to three significant digits.

The ascending rank of all 1170 subplots was determined based on site index and stand biomass within three neighborhoods (blocks) for years 1993 (before harvest) and 2001 (5 yr after planting) (SAS Institute, 2001). Rank values ranged between 1 (best sites) and 390 (worst sites). Ties were assigned the average rank for that set of observations; for example, the number set (22, 23, 24, 24, 25, 26, 26, 26, 27) would be ranked (9, 8, 6.5, 6.5, 5, 3, 3, 3, 1) using this logic. Change in rank was calculated as the rank in 1993 minus the rank in 2001. Change in rank is normally distributed and can be modeled using standard parametric procedures (Eisenbies, 2004).

A $3 \times 3 \times 2$ factorial design was used to evaluate three levels of soil disturbance (heavy, moderate, and minimal), three levels of harvesting residue (Class III, II, and I), and two levels of site preparation (flat-planted and bedded). The hypothesis was that productivity will be least negatively affected on sites that were the least physically disturbed and with sufficient organic matter in the form of harvesting residues (Fig. 3). In addition, we hypothesized that flat-planting previously bedded sites would result in a relative decrease in soil-site productivity.

Change in rank was analyzed for site index (RCSI) and green weight biomass (RCSB) using the general linear model at the $\alpha = 0.1$ level with prior rank as a covariate (SAS Institute, 2001) to assess changes in soil and site productivity as it relates to soil physical disturbance and organic residues. Means separations were determined by Fisher's protected least significant difference. "Statistical slicing" (Schabenberger and Pierce, 2002) was used to address three specific contrasts at the polypedon scale. The contrasts were: (1) Was there a significant difference in the "rank diagnostic" between the bedded and flat planted sites for each specific combination of soil physical disturbance and harvesting residue? (2) Was the change in rank, of site index or biomass, for any combination of soil physical disturbance and harvesting residues significantly different from a reference category among the bedded sites? (3) Was the change in rank, of site index or biomass, for any combination of soil physical disturbance and harvesting residue significantly different from a reference category among the flat-planted sites?

The purpose of the reference category is similar to that of an experimental control. Because the rank method evaluates relative productivity rather than an absolute measure of productivity, a benchmark must be used for comparison. Sites that received minimal disturbance, with moderate amounts of harvesting residues (Class II), were selected as the reference categories for the purpose of this study; however, depending on the research questions, other treatments may potentially be used as benchmarks. The reference category selected for this study assumes that sites that received little or no soil physical disturbance and retained an intact litter layer with scattered slash should be the sites that would best retain their productivity after harvesting traffic.

RESULTS AND DISCUSSION

Disturbance Class Prevalence

Each of the three soil physical disturbance classes represented about one third of the 20-m grid cells for the wet and dry harvests on the entire study site (Table 1). By definition, large machinery or vehicle traffic was not observed to visually affect soil surfaces within the minimal category. The moderate category was 66% undisturbed, and only 10.8% was "heavier" than visibly compressed. Rutting and churning affected 72% of the heavy disturbance category.

Harvesting residue classes among the 20-m grid cells were distributed as 39% Class I, 48% Class II, and 11% Class III (Table 2). The Class I category had almost no bare soil after harvesting (litter layer was intact) and

Table 1. Comparison of the five types of post-harvest soil physical disturbance for the physical disturbance categories (minimal, moderate, heavy), and the percentage of 20-m grid cells placed in each polypedon-scale category.

Disturbance category	Undisturbed	Compressed	Shallow rutted, <30 cm deep	Deep rutted, >30 cm deep	Churned	20-m cells classified
	%					
Minimal	**100.0a†**	**0.0c**	**0.0c**	**0.0b**	**0.0b**	**29.3**
Moderate	**66.9b**	**22.3a**	**5.5b**	**1.1b**	**4.2b**	**35.4**
Heavy	**16.5c**	**11.5b**	**19.3a**	**23.6a**	**29.1a**	**32.4**
Unclassified						**2.9**

† Letters indicate Fisher's least significant differences at the $\alpha = 0.05$ level within column only.

Table 2. Comparison of the five types of organic residues for the harvesting residue disturbance categories (Class I, II, III), the total dry-weight residue biomass, and the percentage of 20-m grid cells placed in each polypedon-scale category.

Disturbance category	Slash piles	Heavy slash	Light slash	Litter	Bare soil	20-m cells classified	Harvest residue
	%						kg m^{-2}
Class I	2.1a†	32.3a	70.8a	96.1a	3.9b	38.8	9.1a
Class II	1.5a	13.9b	51.7b	90.5a	9.6b	47.6	6.9b
Class III	2.2a	11.9b	34.2c	51.2b	48.8a	10.7	5.6c
Unclassified						2.9	

† Letters indicate Fisher's least significant differences at the $\alpha = 0.05$ level within column only.

was 70% covered by light slash or heavier material. The mean total dry biomass of harvesting residues was 9.1 kg m^{-2}. The Class II category had 9.6% bare soil and was 50% covered by light slash with little heavy slash. The total dry biomass of harvesting residues averaged 6.9 kg m^{-2}. The Class III category averaged near 50% bare soil after harvesting, and, despite the amount of bare soil, the mean total dry biomass of harvesting residues was 5.6 kg m^{-2}.

Tiarks (1990) observed no physical disturbance associated with dry-weather harvesting on coarser soils in Louisiana; however, he observed very little undisturbed soil on wet-weather harvested sites (2.7%). On our sites, the minimal disturbance category was also uncommon (6.2%) on wet-weather harvested sites but comprised over 60% of dry-harvested sites (Table 3). Physical disturbance on dry-weather harvested sites was largely restricted to sites with >25% bare soil. The majority of heavy and moderate disturbance classes for the 20-m grid cells occurred on wet-harvested sites. When moderate disturbance occurred on dry-harvested sites, it generally corresponded with bare soil exposure.

These results support the selection of the minimal-Class II category as the reference category for the second and third contrasts in the rank analysis. The minimal disturbance category represents a site where the effects of harvest traffic on soil-site quality should be very small. The Class II category, which averaged 6.9 kg m^{-2} in harvested residues, is consistent with findings of Haines et al. (1975). They reported little additional improvement in 4-yr-old loblolly and slash pine (*Pinus elliottii* Engelm.) stands when harvesting residues of 73, 145, and 290 Mg ha^{-1} were incorporated into the soil (Pritchett and Fisher, 1987).

Table 3. Percentage of the 20-m grid cells for each combination of the soil physical (minimal, moderate, heavy) and harvesting residue (Class I, II, III) disturbance categories occurring within wet- and dry-harvested sites.

Disturbance category	Dry harvested	Wet harvested	Entire study
	%		
Minimal			
Class I	15.4	5.2	9.3
Class II	45.8	1.0	18.8
Class III	3.2	0.0	1.2
Moderate			
Class I	1.9	26.6	16.8
Class II	9.2	13.0	11.5
Class III	17.4	0.4	7.1
Heavy			
Class I	0.2	20.8	12.7
Class II	0.0	28.7	17.3
Class III	0.0	3.9	2.4
Unclassified	6.9	0.4	2.9

Table 4. Post-harvest height at age 5 and estimated site indexes (base age 25) associated with each of the disturbance classes and site preparation.

Disturbance category	Flat-planted	Bedded	Flat-planted	Bedded
	height (m)†		site index (m)†	
Minimal				
Class I	5.12	5.99	21.0Ba‡	24.3Aab
Class II	5.25	5.90	21.1Ba	24.1Aab
Class III	4.83	6.18	22.0Ba	25.9Aa
Moderate				
Class I	5.01	6.43	20.6Ba	26.3Aa
Class II	4.87	6.39	20.8Ba	26.2Aa
Class III	5.25	6.11	21.5Ba	24.8Aa
Heavy				
Class I	4.84	6.12	19.6Ba	24.8Aa
Class II	5.01	6.12	20.5Ba	24.6Aab
Class III	5.10	5.31	21.7Aa	22.0Ab
All categories				
Mean	5.11	6.14	21.0B	24.8A

† Least squares means.
‡ Capital letters indicate significant differences within rows ($\alpha = 0.1$), and lowercase letters indicate significant differences within columns.

Productivity Responses

Mean heights of the third-quartile trees ranged from 4.84 to 6.43 m, and the mean site index ranged from 19.6 to 26.3 m (base age 25) among all disturbance categories after 5 yr of growth (Table 4). Tree heights were 1 m greater on bedded sites versus flat-planted sites, and site indexes were 3.8 m greater. The global analysis of covariance was significant ($P = 0.0001$) for height and site index; however, prior site index was not significant as a covariate ($P > 0.7$). Bedding was the only significant main effect ($P < 0.0001$), and none of the other main effects or interactions were significant.

The global ANCOVA of the RCSI factorial was significant ($P < 0.0001$), and prior rank was significant as a covariate ($P < 0.0001$). There were no significant differences among the three physical disturbance classes on the flat-planted sites, but moderate disturbance resulted in a significant increase in rank relative to the heavily disturbed sites (Fig. 4a). There were no significant differences among the three residue classes for either type of site preparation (Fig. 4b). The mean rank change of the bedded sites (+36.3) was significantly higher than the flat-planted sites (−45.4) (Table 5). The total differential (82) would equate to nearly a one-quartile difference within a pooled distribution of the untransformed site index data.

According to our first contrast, there was a significant difference in site quality response to treatments between the bedded and flat-planted sites on all but the heavily disturbed-Class III sites. Based on the second contrast, the only disturbance combination that outperformed the reference category among the bedded sites was the moderate-Class II category ($P = 0.0952$). There were no significant differences in the third contrast comparing the eight combinations of soil-disturbance and harvest residue to the reference among the flat-planted sites.

The mean green weight biomass ranged from 23.4 to 46.4 Mg ha^{-1} for the range of disturbance categories

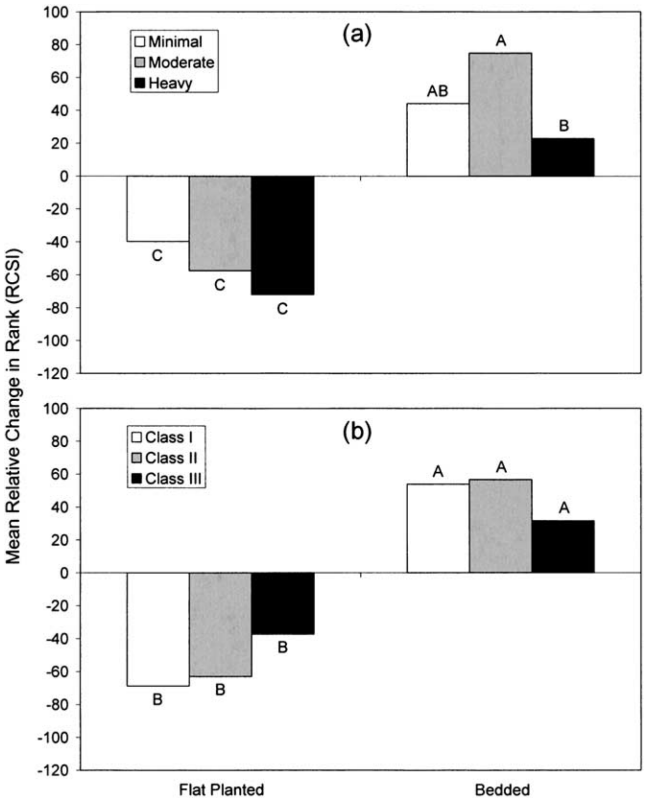

Fig. 4. Relative change in soil-site productivity between rotations based on the change in rank based on site index. (a) Soil physical disturbance categories. (b) Harvesting residue disturbance categories. Different letters indicate Fisher's least significant differences at the α = 0.1 level using prior rank as a covariate.

(Table 6). Mean tree biomass was 7 kg tree^{-1} and 13 Mg ha^{-1} higher on bedded plots versus flat-planted plots. The global ANCOVA was significant ($P <$ 0.0001), as was the main bedding effect ($P < 0.0001$), but prior biomass and site index were not significant as covariates ($P < 0.2537$). Similarly, Tiarks (1990) observed no significant differences in fifth-year heights and diameters for slash pine between wet- and dry-harvested sites in Louisiana, and Scott and Tiarks (2005) reported that by age 18, significant differences between sites were primarily in response to site preparation and fertilization rather than soil disturbances.

Table 6. Post-harvest mean green weight biomass associated with each of the disturbance classes and site preparation.

Disturbance category	Flat-planted	Bedded
	Mg ha^{-1}†	
Minimal		
Class I	23.9b‡	34.5a
Class II	24.1b	34.6a
Class III	26.3b	35.8a
Moderate		
Class I	24.1b	43.5a
Class II	24.7b	46.4a
Class III	24.6b	38.1a
Heavy		
Class I	26.3b	39.1a
Class II	23.4b	39.3a
Class III	37.7a	37.6a
All categories		
Mean	25.3b	38.8a

† Least squares means.
‡ Letters indicate significant differences within rows only (α = 0.1).

The global ANCOVA of the RCSB factorial was significant ($P < 0.0001$), and prior rank was significant as a covariate ($P < 0.0001$). There were no significant differences among the three physical disturbance classes on the flat-planted sites, but moderate disturbance on the bedded sites resulted in a significantly higher change in rank than the minimal sites (Fig. 5a). There were also no significant differences among the three residue classes for either site preparation (Fig. 5b). The mean rank change of the bedded sites (+28.6) was significantly higher than the flat-planted sites (−50.2) (Table 7). As with RCSI, the total differential (79) equates to nearly a one-quartile difference within a pooled distribution of the untransformed biomass data.

According to our first contrast, the change in rank on the bedded sites was significantly higher than the flat-planted sites on all but the heavily disturbed-Class III sites and the minimal-Class III sites. Based on the second contrast, the only disturbance combination that out-performed our reference category of the bedded sites was the moderate-Class II category ($P = 0.0514$). Significant differences were not found in the third contrast comparing the other combinations of soil-distur-

Table 5. Relative change in soil/site productivity between rotations for combinations of soil physical disturbance, harvesting residue, and site preparation based on the change in rank of site index (RCSI) (α = 0.1).

Disturbance category	Flat-planted	Bedded	Contrast 1†	Contrast 2‡	Contrast 3§
	RCSI				
Minimal					
Class I	−48.9	25.3	**	NS	NS
Class II	−48.7	25.6	**	Reference	Reference
Class III	−21.3	81.8	*	NS	NS
Moderate					
Class I	−65.1	85.5	*	NS	NS
Class II	−63.1	98.0	*	**	NS
Class III	−44.1	41.0	**	NS	NS
Heavy					
Class I	−92.4	50.4	*	NS	NS
Class II	−77.4	46.3	*	NS	NS
Class III	−44.6	−30.0	NS	NS	NS
All categories					
Mean	−45.4	36.3	*	N/A	N/A

† Contrast 1: Significant response to bedding.
‡ Contrast 2: Significantly different from the bedded, minimal-class II reference.
§ Contrast 3: Significantly different from flat-planted, minimal-class II reference.

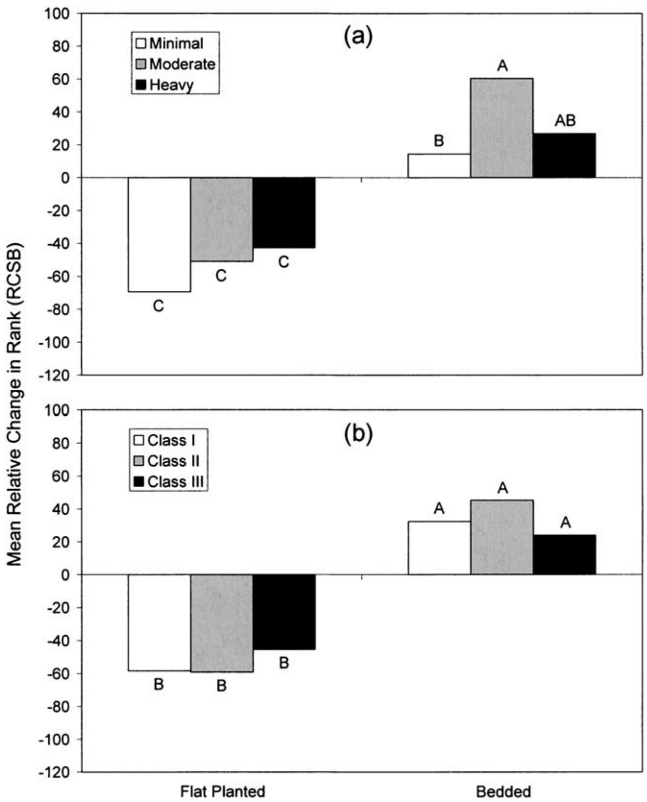

Fig. 5. Relative change in soil-site productivity between rotations based on the change in rank based on stand biomass. (a) Soil physical disturbance categories. (b) Harvesting residue disturbance categories. Different letters indicate Fisher's least significant differences at the α = 0.1 level using prior rank as a covariate.

bance and harvest residue with the reference among the flat-planted sites.

Rank Diagnostic Interpretation

According to the RCSI and RCSB diagnostic variables, moderate physical disturbance coupled with bedding seems to benefit soil-site productivity (Fig. 4 and 5). Lister et al. (2004) noted that bulk densities were lower, albeit not significantly, on moderately disturbed-bedded sites on this experimental area. Aust et al. (1998) noted that soil water field capacities were higher on the moderately disturbed sites, which may indicate increased localized water retention. These sites suffered drought conditions for three of the first 5 yr of growth (Eisenbies et al., 2004), and water retention may have been a particularly important factor.

The second contrasts in the RCSI and RCSB analyses indicate that none of the disturbance categories significantly underperformed relative to the reference category (minimal-Class II disturbance combination) (Tables 5 and 7). However, the moderate-Class II sites outperformed the reference, which indicates that moderate disturbance may improve relative productivity absent of excessive bare soil or excessive slash. Moderate physical disturbance can be beneficial to plant growth, although the threshold where it becomes detrimental can be narrow (Greacen and Sands, 1980; Kozlowski, 1999). Lister et al. (2004) found that average pine volume after 2 yr was 30 to 50% greater in compressed soils than minimal or heavily disturbed soils. Among the flat-planted sites, there was a trend for the more heavily disturbed sites to have lower relative soil-site productivity. However, in terms of the main disturbance effects, this study revealed few statistically significant relationships in spite of the fact that the classes do represent distinct levels of physical disturbance.

We did not observe any significant effect or meaningful patterns of change in soil-site productivity among residue categories. The potential benefits of increased organic matter on overall productivity are great, although they are not entirely predictable. Childs et al. (1986) showed that increasing residues can result in an upward trend of moisture availability, but the pattern is not smooth because the nature and quality of the organic matter also influences nutrition and moisture relationships. In addition, excessive residues can interfere with proper bed formation (Terry and Hughes, 1975), and these sites had large amounts of harvesting debris incorporated in the upper 30 cm of soil (Lister et al., 2004).

After operationally realistic harvesting, the quantity

Table 7. Relative change in soil/site productivity between rotations for combinations of soil physical disturbance, harvesting residue, and site preparation based on the change in rank of stand biomass (α = 0.1).

Disturbance category	Flat-planted	Bedded	Contrast 1‡	Contrast 2§	Contrast 3¶
	RCSB†				
Minimal					
Class I	−71.1	0.3	**	NS	NS
Class II	−60.9	11.0	*	Reference	Reference
Class III	−75.3	32.8	*	NS	NS
Moderate					
Class I	−70.4	59.7	*	NS	NS
Class II	−40.1	83.5	*	**	NS
Class III	−41.6	37.9	*	NS	NS
Heavy					
Class I	−33.5	37.1	**	NS	NS
Class II	−76.4	41.6	*	NS	NS
Class III	−16.5	1.9	NS	NS	NS
All categories					
Mean	−50.2	28.6	*	N/A	N/A

† RCSB, change in rank of stand biomass.
‡ Contrast 1: Significant response to bedding.
§ Contrast 2: Significantly different from the bedded, minimal-class II reference.
¶ Contrast 3: Significantly different from flat-planted, minimal-class II reference.

of residues on each of the disturbance classes was greater on average than 5.3 kg m^{-2} for all combinations of physical disturbance and harvest residue categories. This may not be sufficiently below the 7 kg m^{-2} threshold reported by Haines et al. (1975) for loblolly and slash pine flatwoods to cause a strong response at the polypedon scale. In addition, wet-weather harvesting resulted in larger amounts of harvesting residue (mostly in the form of light and heavy slash) on the site and less bare soil (Eisenbies et al., 2004), so areas that had heavy soil physical disturbance retained a larger amount of harvesting residues. This is attributed to the fact that the loggers who harvested this study (acting as they would if this were a commercial harvest) topped the trees by hand on the wet-harvested sites to reduce drag and improve traction during skidding. In contrast, whole trees were skidded to a delimbing gate near the landing on the dry-harvested sites.

The benefits of bedding poorly drained pine flats are well established (Schultz and Wilhite, 1974; Terry and Hughes, 1975; Gent et al., 1983; McKee et al., 1985; Morris and Lowery, 1988). Bedding enhances microsite drainage, restores soil physical properties, and increases the availability of important nutrients such as nitrogen. Change in site index and biomass rank was significantly higher on bedded plots versus the flat-planted equivalents with the exception of the heavily disturbed-Class III sites (Tables 5 and 7). The cause of this discrepancy was not only because these sites did not respond as well to bedding but was also due to the fact that the flat-planted, heavily disturbed-class III plots seemed to have higher production relative to the other disturbance categories. A prominent feature of these heavily disturbed sites was the presence of ridges between the ruts that formed "pseudo-beds," which were opportunistically used by the hand planters. Heavy disturbance can also suppress competition (Aust et al., 1997; Lister et al., 2004; Murphy and Firth, 2004). This may explain why trees grew well on the flat-planted plots, but after the additional traffic associated with the shearing and bedding treatments, the benefit of the pseudo-beds could have been negated. In addition, the heavily disturbed sites tended to reside close to the landing and higher in elevation and initial site quality (Table 8). Harvest equipment operators probably avoid depressions in wet weather to prevent bogging. The heavily disturbed-Class III combination was rare on the whole and comprised <4% of the wet harvested 20-m grid cells and <3% of the entire 60-ha study. At the operational scale, there were no significant differences in the change in soil-site productivity between wet- and dry-weather harvesting when bedding was used (Eisenbies, 2004); however, there were differences in actual biomass accumulation (Eisenbies et al., 2004).

Trees grew better on a relative basis on the moderately disturbed sites than the minimal or heavily disturbed sites after bedding (Fig. 4 and 5). In addition to the increased availability of nutrients such as nitrogen (Burger and Pritchett, 1988), another explanation may be that competition can be initially suppressed on wet-harvested sites (Aust et al., 1997; Lister et al., 2004; Murphy and Firth, 2004). A second explanation could be that bed formation is best on moderately disturbed sites. Bed quality can be profoundly important for tree survival and growth on poorly drained sites (Terry and Hughes, 1975; Aust et al., 1993; Conner, 1994). Minimally disturbed sites, which tend to reside at lower relative elevations, may be too wet to form proper beds. In addition, the bedding plows may not work as efficiently on heavily disturbed sites with irregular surfaces due to rutting or on wet-weather harvested sites where excessive debris (Eisenbies et al., 2004; Lister et al., 2004) may interfere with bedding quality (Terry and Hughes, 1975).

Disturbance-Independent Site Attributes

In addition to the growth parameters, four disturbance-independent site attributes were evaluated for the disturbance categories: (1) the pre-harvest rank of site index and (2) stand biomass, (3) the distance to the logging deck, and (4) the relative elevation. Analysis of pre-harvest rank indicates that there may be a propensity for higher quality sites, sites that are closer to the landing, and sites in slightly higher relative elevations to become heavily disturbed (Table 8). Class III harvest residue disturbances occurred significantly closer to the landing, but this was the only significant difference found among these attributes with regard to the residue cate-

Table 8. Comparison of disturbance-independent site attributes.

Disturbance category	Pre-harvest site index	Pre-harvest biomass	Distance to landing	Relative elevation‡
	Rank†		m	
Soil disturbance category				
Minimal	231A¶	219A	170A	2.2A
Moderate	195AB	194AB	154A	2.6AB
Heavy	166B	173B	121B	3.0B
Harvesting residue category				
Class I	181a	190a	162a	2.7a
Class II	195a	189a	155a	2.7a
Class III	216a	207a	126b	2.5a
Heavy-Class III combination				
Mean	146	159	91	3.3
All sites				
Mean	197	195	148	2.6

† Lower numbers are assigned to sites with higher initial site index or average tree biomass.
‡ Elevation above lowest point within a 30-ha neighborhood as determined from a 30-m digital elevation model.
¶ Capital letters indicate Fisher's least significant differences within column only for the main soil physical disturbance effect. Lower-case letters indicate Fisher's least significant differences within column only for the main harvesting residue effect ($\alpha = 0.1$).

gories. Finally, the heavy disturbance-Class III sites were the top pre-harvest production levels, were closest to the landings, and had the highest relative elevation among the specific soil disturbance harvesting residue combinations.

Long-Term Implications

The use of early stand data for forecasting long-term results is often limited. It is not possible to conclude that these results will predict results at the end of the rotation without qualification; however, we believe that one limited, long-term inference can be drawn. Our logic is that if an impact is observed at stand closure, the long-term manifestation will have one of three outcomes (Miller et al., 2004). One outcome would entail a treatment effect causing an early reduction in stand growth that is maintained until stand closure, at which point all stands proceed to grow at similar rates but may not alter site productivity. This impact is indicative of different resource allocation rates associated with different treatments. A second outcome entails a permanent impact to soil-site quality whereby the reduction in soil-site quality is likely to continue in current and future rotations. The last outcome entails a temporary response, whereby the initial impact fades over the course of the rotation. Indeed, Burger and Kluender (1982) hypothesized that large initial gains due to the types of site preparation could disappear by the end of the rotation, and this pattern was observed in a rotation-length study by Cerchiaro (2003).

An outcome we are unlikely to observe is a divergence between treatments after stand closure that have thus far responded the same; specifically, treatment responses that are the same today are likely to remain the same in the future. Applying these concepts to our results, it is impossible to conclude whether the change in site productivity of the flat-planted sites relative to the bedded treatment would follow a specific outcome as described by Miller et al. (2004). However, it is unlikely that we will observe a divergent pattern between stands that have reached canopy closure, and we have responded similarly up to this point in the rotation. Thus, it is reasonable to conclude that relative to the preferred condition of the reference treatment (minimal-Class II), the soil-site productivity of more disturbed areas that are not different today and will not be significantly different in the long-term.

CONCLUSIONS

There were no significant changes detected in soil-site productivity between the first and second rotation in response to increasing soil physical disturbance or increasing levels of harvest residues after typical logging operations in wet- and dry-weather 5 yr after stand replacement. There were significant differences in productivity between flat-planted and bedded sites except in one case. Based on site index and biomass rank changes, bedding restored productivity in all cases except for the most heavily disturbed sites, and the lack of response on those sites was caused by the enhanced growth on the flat-planted sites due to pseudo-bedding and poor bed formation. However, these heavily disturbed sites, with large amounts of bare soil after harvesting, represented a very small proportion (about 5%) of the entire harvesting units. Disturbance occurs as a mosaic. Heavier disturbance features (compaction, rutting, and churning) exist in conjunction with less severe disturbances at scales most likely to influence stand growth. This may be why we have not seen many operational results that establish the link between specific disturbance types (e.g., compaction, rutting, and churning) and diminished productivity in spite of the known effects these disturbances have on soil properties.

Moderately disturbed sites, without excessive bare soil or excessive slash, were the highest performing sites after 5 yr; however, a full rotation is necessary to ascertain if our observations represent a true long-term response. The distribution of harvesting residues seems to be adequate to maintain site fertility but in some cases may interfere with bed formation. Overall, these wet pine flats have proven to be resilient when site prepared. None of the more heavily disturbed areas that received site preparation underperformed relative to the minimal-Class II reference, which would reasonably be considered the operational desirable outcome of harvesting.

The main foci of harvesting BMPs have been on protecting water quality and maintaining site productivity. Across a broad range of studies and forest types on the Southern Coastal Plain, one of the main concerns has to do with soil physical and organic matter disturbance associated with large machinery and vehicle traffic. However, for wet pine flats, drainage seems to be a much more important factor controlling soil-site productivity and pine growth. This study indicates that (1) not all BMPs designed to protect site productivity by limiting soil disturbance are universally necessary, and (2) BMP evaluations should consider site preparation methods used by intensive forest management practices that help remediate site disturbance (e.g., bedding). There are sites that do not respond favorably to disturbance, but wet pine flats, with similar characteristics to our sites (e.g., high fertility, shrink-swell clays), may be suited for harvesting during wet weather as long as they can be accessed economically and receive appropriate site preparation.

Under operationally realistic conditions, logger behavior varied depending on wet and dry harvesting conditions. In dry weather, loggers skidded and delimbed trees near the landing. Tree limbs were removed where they were felled in wet weather to provide additional flotation for the equipment and to reduce drag during skidding. Additionally, skidder operators avoided depressional areas to prevent bogging, thus concentrating disturbance on sites with higher relative elevations. Logger behavior is an important consideration in studies of this nature. Studies should take account of logger actions as well as possible so that research results are most useful to land managers.

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