Changes in site productivity and the recovery of soil properties following wet- and dry-weather harvesting disturbances in the Atlantic Coastal Plain for a stand of age 10 years

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Abstract: Wet-weather logging can cause severe soil physical disturbances and redistribute residues. Although some research indicates negative effects of such disturbances on individual tree growth, the long-term resilience and resistance of soils and the ameliorative effects of site preparation are not fully understood. Three 20 ha loblolly pine (*Pinus taeda* L.) plantations located on fertile wet pine flats on the coastal plain of South Carolina were subjected to five treatment combinations of harvest (wet and dry) and site preparation. Mean tree heights were 10.2–11.5 m, and stand biomass ranged between 95 and 143 Mg/ha. A rank diagnostic indicates that wet-weather harvesting did not significantly change site productivity between rotations, and bedding improved site productivity. At the polypedon scale (0.04 ha), there were no significant differences in tree height, biomass, or the rank diagnostic among classes of soil physical disturbances or harvesting residues when bedding was employed. On nonbedded sites, some levels of disturbance appeared to be superior to minimally disturbed sites. Based on 10 year results, wet pine flats are apparently resistant and resilient to the effects of wet-weather harvesting.

Résumé : Par temps pluvieux, les opérations forestières peuvent causer des perturbations physiques sévères dans le sol et redistribuer les déchets de coupe. Bien que certaines recherches aient rapporté les effets négatifs de telles perturbations sur la croissance des arbres, la résistance et la résilience à long terme des sols ainsi que les effets bénéfiques de la préparation de terrain ne sont pas entièrement compris. Trois plantations de pin à encens (*Pinus taeda* L.) de 20 ha, situées sur les platières humides et fertiles de pin dans la plaine côtière de la Caroline du Sud, ont été soumises à cinq combinaisons de traitements de récolte (humide et sec) et de préparation de terrain. La hauteur moyenne des arbres était de 10,2 à 11,5 m et la biomasse des peuplements variait de 95 à 143 Mg/ha. Un diagnostic d'ordination indique que la récolte par temps pluvieux n'a pas significativement modifié la productivité de la station entre les rotations et que la plantation sur ados a amélioré la productivité. À l'échelle du polypédon (0,04 ha), il n'y avait pas de différences significatives dans la hauteur des arbres, la biomasse ou le diagnostic d'ordination entre les classes de perturbation physique des sols ou les déchets de coupe lorsque la plantation sur ados avait été utilisée. Dans les plantations où la plantation sur ados n'avait pas été utilisée, certains niveaux de perturbation semblaient supérieurs à celui des stations peu perturbées. Sur la base de résultats portant sur 10 années, les platières humides de pin sont apparemment résistantes et résilientes aux effets de la récolte par temps pluvieux.

[Traduit par la Rédaction]

Introduction

According to the Food and Agriculture Organization (FAO) of the United Nations, the total forest area worldwide was slightly less than 4 billion hectares (Food and Agriculture Organization of the United Nations (FAO) 2005). In addition, conversion of forests to other land uses is occurring at a rate of about 13 million hectares per year, suggesting that our reliance on intensively managed plantation forests for timber and wood fiber production will increase (Sedjo 1999). Currently, the vast preponderance of biomass produced is extracted from natural forests. While forest plantations managed for timber production account for less than 3% of the total forest area, they are likely the only feasible way to meet the demand for wood fiber in the future (FAO 2005; Fenning and Gershenzon 2002).

In the United States, advances in silviculture, economic pressures, and changing land values have resulted in an increasing dependence on a smaller land base to keep up with the demand for wood fiber (Fox 2000). Nearly 25 million hectares are managed as intensive pine plantations in the southeastern US. Southern yellow pine species represents approximately 30% of US wood fiber production (Conner and Hartsell 2002). By 2050, nearly two-thirds of softwood production is expected to come from plantation forests in the US (USDA Forest Service (USDA-FS) 2000).

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For several decades there has been scientific concern that the productivity of intensively managed forests may decline and that intensive forestry practices may not be sustainable. The increased inputs and cultural activities, coupled with shortened rotations, result in greater vehicle trafficking and forest disturbance. Studies of trafficking disturbance have shown negative effects on soil properties and reductions in tree growth and survival (Aust et al. 1995; Lockaby and Vidrine 1984; Moehring and Rawls 1970; Youngberg 1959). Harvesting traffic may cause severe impacts to soil surface, including compaction, rutting, and churning (characterized by soil mixing and smearing, but with little compaction), which may reduce porosity or alter site hydrology (Greacen and Sands 1980; Kozlowski 1999; Miwa et al. 2004; Sheriff and Nambiar 1995). Additional soil impacts include erosion, nutrient loss, and organic-matter disturbance. However, in spite of ample literature that shows forest practices can negatively affect soil chemical and physical properties tied to tree growth, the direct link between forest operations and productivity decline has been difficult to establish (Burger 1996; Morris and Miller 1994; Worrell and Hampson 1997).

These scientific concerns have resulted in a variety of measures meant to reduce harvesting disturbances, particularly during wet weather, when soil disturbances are visually more severe. Although forestry best management practices (BMPs) are primarily designed to protect water quality, many states expect that the limits on soil rutting and compaction will have a secondary effect of protecting long-term productivity (Aust and Blinn 2004). However, several considerations remain. The fact that a sufficient stockpile cannot be maintained through the wet season to supply mills means that dry-weather harvesting is not always feasible. Also, BMP inspections often rely on visual assessments of soil disturbances, which may not necessarily be indicative of the actual productivity potential of a site. In addition, BMP requirements generally do not consider the resilience of some sites to certain types of disturbance or the role site preparation can play in ameliorating site conditions (Miwa et al. 2004). Given the potentially high costs of some BMPs and site preparation implementations (Cubbage 2004), their efficacy toward the goal of protecting site productivity should be carefully considered.

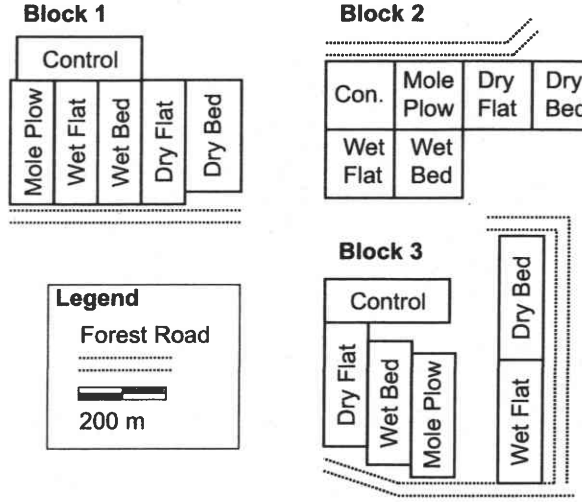
The objectives of this paper are, first, to evaluate if wet-weather harvesting diminishes soil and (or) site productivity after stand closure, and if so, whether site preparation can remediate a site in the most operationally realistic setting possible. Second, to evaluate whether gradients of soil physical disturbances and harvesting residues incurred during operationally realistic harvesting alter site productivity and key soil properties at the polypedon scale, and if so, whether site preparation will remediate these specific disturbances.

Materials and methods

Site description

The study site is located on wet pine flats (Messina and Conner 1998) on the Atlantic Coastal Plain in Colleton County, South Carolina. The topography is flat to gently rolling marine terraces dissected by drainages. The soil parent material consists of marine and fluvial sediments and features the phosphatic Cooper Marl (Stuck 1982). Soils are

Fig. 1. Division of each 20 ha block into individual 3.3 ha treatment plots, comprising the basic study design.



poorly to somewhat poorly drained, and have an aquic moisture regime. Regionally, these sites are considered highly productive and are often intensively managed for the production of loblolly pine (*Pinus taeda* L.).

Three, 20 ha, bedded, loblolly pine plantations were selected as blocks in 1992 based on similar age (20–25 years), soil, and hydrologic conditions. Soils primarily consist of the Argent (US, Typic Ochraqualf; FAO–WRB, Alic Gleysol) (57%), Coosaw (US, Arenic Hapludult; FAO–WRB, Haplic Luvisol) (15%), Santee (US, Typic Argiaquoll; FAO–WRB, Mollic Gleysol) (13%), and Yemassee (US, Aeric Ochraquult; FAO–WRB, Alic Planosol) (14%) series; the US and FAO World Reference Base for Soil Resources (FAO–WRB) taxonomic descriptions are included in parentheses. However, the sites are similar enough that there is no differentiation in their operational management. 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).

Treatment descriptions

Five ~3.3 ha treatment areas were laid out as individual harvest units within each block including separate decks and skid trails (Fig. 1). A sixth area in each block consisted of a no-harvest control, and was not used in this portion of the experiment. Prior to harvest each 3.3 ha treatment area was overlain with a 20 m × 20 m grid. Within each 0.04 ha 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.

Ditches (<100 cm depth) were located along the road at the narrower ends of each treatment plot (blocks 1 and 3) or along the roadside edge of the plots (block 2). These ditches facilitate surface drainage immediately after rainfall, but have little influence on subsurface drainage because of the large size of the treatment plots and low hydraulic conductivities.

A range of soil physical and harvesting residue disturbances were induced at the "operational scale" within each block using dry- and wet-weather harvesting. In the fall of 1993, two randomly selected plots on each block were dry-weather harvested. In the spring of 1994, the remaining three plots on each block were harvested in wet conditions with the goal of maximizing soil disturbance. Harvesting was performed by conventional commercial logging operations using mechanized fellers and wide-tired buncher/grapple skidders. The logger was instructed to treat the individual sites as they normally would for the site conditions that were encountered. Specifically, no effort was made to alter logger behavior. Disturbances were applied in this manner to ensure that the degree and distribution of both soil physical and harvesting residue disturbances would be operationally realistic.

Soil physical and harvesting residue disturbance at the polypedon-scale was evaluated immediately after harvesting (Aust et al. 1998*a*). Site disturbances associated with harvesting operations were characterized for the 20 m grid by visually determining soil physical disturbance and harvesting residue disturbance using methods described in detail by Eisenbies et al. (2005). Soil physical disturbance was categorized as either minimal (generally characterized by no visible soil physical disturbance), moderate (generally characterized by compression tracks although some rutting is possible), or heavy (generally characterized by rutting and churning). Harvesting residue disturbance was categorized as either class I (litter with large amounts of slash), class II (primarily litter), or class III (greater than 25% bare soil). Each residue category equates to approximately 9.1, 6.9, and 5.6 kg/m^2, respectively (Eisenbies et al. 2005). The procedures utilized were meant to serve as a systematic means for differentiating between degrees of disturbance in a manner similar to visual determinations made by state BMP inspectors.

Three levels of mechanical site preparation were applied in 1995: no mechanical site preparation (flat planting), conventional bedding, and an experimental mole plow treatment. The purpose of the mole plow treatment was to facilitate water table equilibration via subsurface drainage in the argillic horizon for areas where rutting and churning may have disrupted normal drainage. Bedded sites were sheared and drum chopped prior to bed installation. Mole plowing was performed in October 1995 and bedding in November 1995 using a mole-shank and modified bedding plow. Thus, there were five treatments at the operational level: dry-harvested and flat-planted (DF), wet-harvested and flat-planted (WF), dry-harvested and bedded (DB), wet-harvested and bedded (WB), and wet-harvested, mole plowed and bedded (WMB).

All sites received chemical weed control in the form of imazapyr (1.2 L/ha) and glyphosate (5.6 L/ha) was applied to each harvested unit in July 1995. The sites were hand planted in February 1996 with bare-root 1–0 stock, best first generation, open-pollinated family, loblolly pine seedlings. 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.

Height and diameter at breast height (DBH) of all trees within the 0.008 ha subplots were measured prior to harvesting. Inventories of height and DBH in the current rotation were conducted at the 2, 5, and 10 year intervals for the same 0.008 ha subplots across the entire study area. Supplemental height and DBH measurements were also made after 7 years of growth from a representative subset within each treatment plot. Site indexes (base age 25 years) were calculated at age 10 years based on the height of a dominant or codominant tree nearest each 0.008 ha subplot center using equations developed for a range of loblolly pine site types (Carmean et al. 1989). Green weight biomass was calculated as a function of height and DBH (Bullock and Burkhart 2003; Phillips and McNab 1982). Changes in soil and (or) site productivity were evaluated using a ranking procedure described by Eisenbies et al. (2005, 2006) with one minor modification: subplot ranking was based on a proportional 0 to 1 scale.

A random subset of 71 plots were used to characterize selected soil properties after the fifth growing season, and stratified based on soil disturbance and harvesting residues. Kelting et al. (1999) identified several key soil properties affecting seedling growth following harvesting disturbance. Soil bulk density, macroporosity, and hydraulic conductivity were determined from 100 cm^3 intact soil cores taken from the A horizon using a core sampler (AMS Inc., American Falls, Idaho). Macroporosity was determined gravimetrically after applying a tension of 4.9 kPa for 24 h (Topp et al. 1993). Saturated hydraulic conductivity was measured using a constant head apparatus. Bulk density was determined after oven drying (105 °C). Oxidation depth was assessed along the planting rows using 5 mm steel rods inserted to the argillic horizon, or to a maximum of 70 cm for deeper soils during the same period as the nitrogen mineralization sampling (Carnell and Anderson 1986). Rods were inserted in October 2001 and removed in October 2003. Net nitrogen mineralization was measured using the buried bag method (Eno 1960). Eight subsamples per plot were collected using a 5 cm push probe at approximately monthly intervals between February 2002 and 2003 (sixth growing season). Bags were buried to a depth of 25 cm within the tree rows. Inorganic N was subsequently extracted from ground and sieved (2 mm) samples using a 2 mol/L KCl solution and analyzed for nitrate and ammonium using an autoanalyzer (Bran-Luebbe TRAACS 2000, Buffalo Grove, Illinois).

Statistical analysis

To address the operational-scale (3.3 ha) objective, the hypotheses that site index, biomass, and the rank diagnostics do not differ among the five treatments were evaluated at the $\alpha = 0.10$ level using the general linear model (SAS Institute 2002–2004). Height, biomass, and rank of the initial stand, as well as stem density of the current stand, were evaluated as covariates. Means separations were determined by Fisher's protected least significant difference. The hypothesis that the treatment by time interactions of the five treatments did not differ was evaluated using repeated measures protocols in the mixed model (SAS Institute 2002–2004). Four covariance structures were considered: compound symmetry, heterogeneous compound symmetry, autoregressive, and heterogeneous autoregressive. A model using heterogeneous autoregressive covariance structure was ultimately selected based collectively on the fit statistics

Table 1. Comparison of treatment height, site index, stand biomass, and stem density at the operational scale (3.3 hectares per treatment plot).

Treatment	Height (m)	Site index (m)*	Stand biomass (Mg/ha)	Stem density (trees/ha)
DF	10.2b	19.0b	95c	1450c
WF	10.2b	19.0b	114b	1860a
DB	10.6b	19.6b	119b	1740ab
WB	10.8ab	20.1ab	13ab	1670b
WMB	11.5a	21.3a	143a	1760ab

Note: DF, dry-harvested and flat-planted; WF, wet-harvested and flat-planted; DB, dry-harvested and bedded; WB, wet-harvested and bedded; and WMB, wet-harvested, bedded, and mole-plowed. Letters adjacent to the numbers in the columns indicate significant differences within columns at the $\alpha = 0.10$ level using Fisher's LSD.

*Base age 25 years.

provided by the SAS mixed model (i.e., –2 Log-Likelihood, AIC, AICC, and BIC).

A 3 × 3 × 2 factorial design was used to test the hypothesis that specific soil physical disturbances, harvesting residues, and site preparation have no effect on height, biomass, or the rank diagnostic (as an indicator of site productivity) at the polypedon scale. Three levels of soil disturbance (heavy, moderate, and minimal), three levels of harvesting residue (classes III, II, and I), and two levels of site preparation (flat-planted and bedded) were used. Change in rank was analyzed for both site index (RCSI) and green weight biomass (RCSB) using the general linear model at the $\alpha = 0.10$ level, with prior rank as a covariate (SAS Institute 2002–2004). "Statistical slicing" (Schabenberger and Pierce 2002) was used for three contrasts to address the hypothesis: (1) Did bedding significantly alter the site productivity as indicated by the rank diagnostic for each specific combination of soil physical disturbance and harvesting residue? (2) Did any combination of soil physical disturbance and harvesting residue differ from a reference category among the bedded sites? (3) Did any combination of soil physical disturbance and harvesting residue differ from a reference category among the flat-planted sites? The minimally disturbed, class II sites were used as the reference category because conventional wisdom would consider it to be the most desirable postharvest condition, specifically, an absence of compaction or rutting, and the presence of organic residues on the surface.

The hypotheses that soil properties would not change at the operational and polypedon scale were evaluated using either a 3 × 3 × 2 factorial as mentioned previously, or a 2 × 2 factorial using two levels of harvesting, and two levels of site preparation. Due to the equivalent growth and hydrologic responses between the bedded and mole plowed sites (wet harvested only) (Eisenbies et al. 2006; Xu et al. 2002), we pooled these two operations for the purposes of utilizing the factorial designs. Both designs were analyzed in the general linear model, and means separations were conducting using Fisher's protected least significant difference (SAS Institute 2002–2004).

Results and discussion

Soil disturbances

In a review of harvesting disturbance from the 1960s to the 1980s, Reisinger et al. (1988) reported that >63% of logging areas remain undisturbed after harvesting operations. In general, forest managers and state regulators try to limit or preclude trafficking disturbance such as rutting or churning on all sites. We attempted to maximize soil physical disturbances for the purposes of this study. At the time of treatment installation, deep rutting was considered excessive in South Carolina when 20%–25% of the site is affected (Tim Adams, S.C. Forestry Commission, personal communication, 1994). Wet-weather harvesting resulted in substantial soil physical disturbance and harvesting residue redistributions (Eisenbies et al. 2006). While soil compaction occurred on less than 10% of dry-weather harvested sites, wet-weather harvested sites were over 60% disturbed including compaction, rutting, and churning. Postharvest residues ranged between 6 and 10 kg/m^2 across the site, and greater quantities were found on wet-harvested sites because loggers topped trees as they were felled on wet-harvested sites, whereas whole trees were skidded to delimbing gates on dry harvested sites (Eisenbies et al. 2002).

Operational scale

The effects of wet-weather harvesting at the scale at which stands are managed (multiple hectares) is evaluated at the operational scale (~3 ha). At 10 years of growth, mean height ranged between 10.2 and 11.5 m among the five operational scale treatments, and site indexes ranged between 19.0 and 21.3 m (base age 25 years) (Table 1). Prior site index (or height) was not significant as a covariate (P = 0.177). Mean stand biomass ranged between 95 and 143 Mg/ha and was highest on three bedded treatments regardless of harvest season. Stem density (P = 0.080) was significant as a covariate, but prior stand biomass (P = 0.730) was not at the $\alpha = 0.10$ level. There was little differentiation in height growth between treatments. The WMB performed better than the DB, DF, and WF treatments, but there were no other significant differences detected. In general, bedded sites had significantly greater tree biomass than flat-planted sites. However, there were few significant differences detected between wet- and dry-harvested sites that received the same site preparation. The only notable difference was between the WMB treatment (143 Mg/ha) and the DB treatment (119 Mg/ha).

After an initial differentiation between treatments, the trend in height and biomass growth patterns was neither divergent or convergent (Fig. 2). Repeated measures analysis indicates there are significant differences in the slope (treatment by time interaction) of the trends for height (P = 0.088), but not biomass (P = 0.254). Although the lines ap-

Fig. 2. Height and biomass growth curves for five combinations of harvesting and site preparation. Treatments: DF, dry-harvested and flat-planted; WF, wet-harvested and flat-planted; DB, dry-harvested and bedded; WB, wet-harvested and bedded; and WMB, wet-harvested, bedded, and mole-plowed.

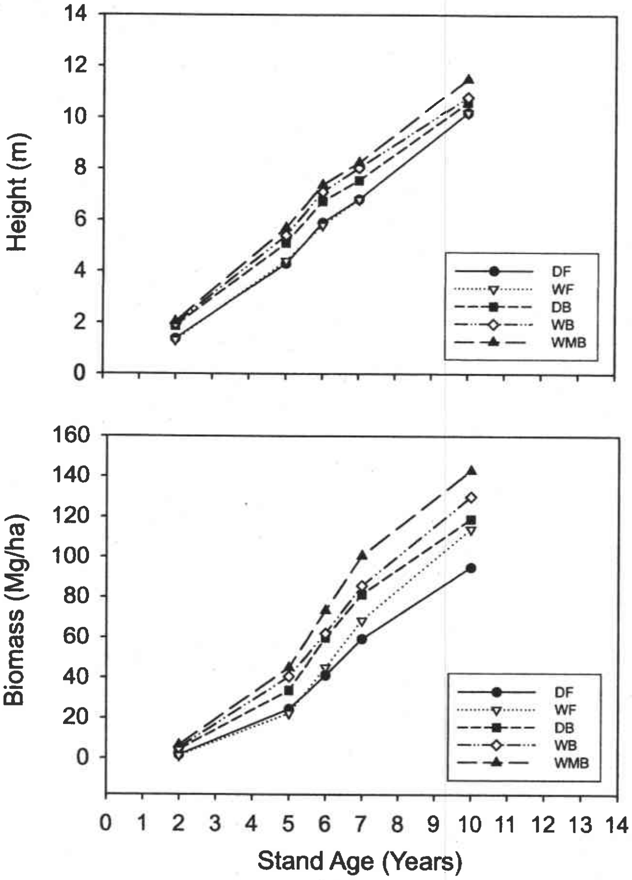
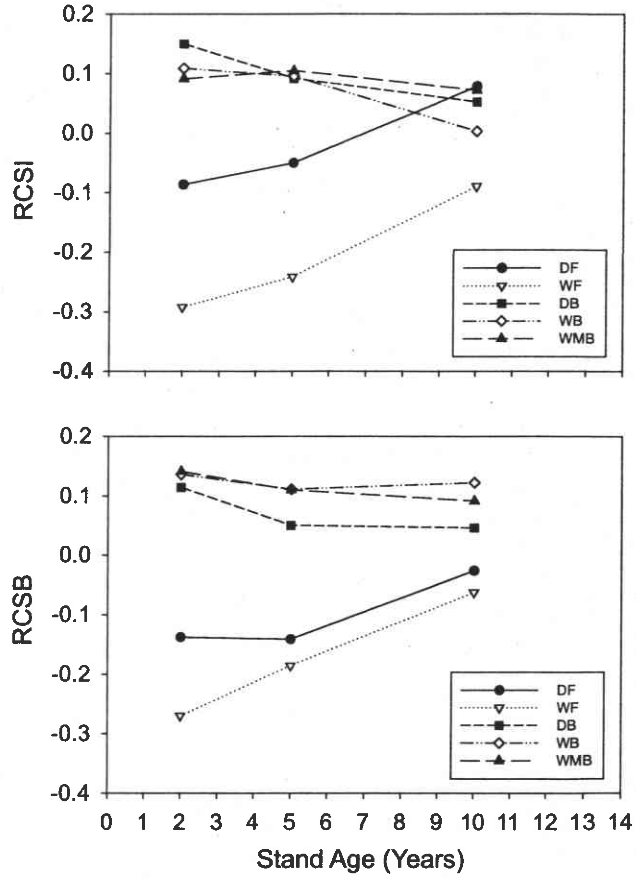


Fig. 3. Relative change in soil site productivity between rotations for five combinations of harvesting and site preparation as reflected by change in rank based on site index (RCSI) and stand biomass (RCSB). Treatments: DF, dry-harvested and flat-planted; WF, wet-harvested and flat-planted; DB, dry-harvested and bedded; WB, wet-harvested and bedded; and WMB, wet-harvested, bedded, and mole-plowed.



pear to diverge with regards to biomass, the variability within a given time step overshadows any treatment by time interactions. Morris and Lowery (1988) attribute such parallel patterns with sites that have maintained site productivity as defined by the ability of the site to sustain a given growth rate.

Unfortunately, differences in height and biomass may be confounded by differences in site quality. Although prior production was not significant as a covariate in the analysis of height and biomass, there were detectible differences between treatment plots prior to treatment installation (Eisenbies et al. 2005). Change in rank allows relative changes in soil-site quality between rotations to be evaluated while controlling confounding factors due to changes in genetics, climate, and silvicultural practices (Eisenbies et al. 2005, 2006).

The trends in the RCSI and RCSB rank diagnostics indicate a convergence in the relative change in soil and (or) site productivity of the five treatments for both site index ($P = 0.002$) and biomass ($P = 0.014$) (Fig. 3). As treatments become less differentiated, the diagnostics approach zero. At age 10 years, there were no significant differences in the change in rank based on site index (height) or biomass among the bedded sites (Table 2). Among the flat-planted sites, there was a significant difference detected between wet and dry harvesting with regards to the RCSI diagnostic,

Table 2. Relative change in soil and (or) site productivity between rotations for five combinations of harvesting and site preparation as reflected by change in rank based on site index (RCSI) and stand biomass (RCSB).

	RCSI*	RCSB
Treatment	Change in rank	
DF	0.079a	–0.026bc
WF	–0.089b	–0.062c
DB	0.053a	0.046ab
WB	0.003ab	0.122a
WMB	0.072a	0.091a

Note: DF, dry-harvested and flat-planted; WF, wet-harvested and flat-planted; DB, dry-harvested and bedded; WB, wet-harvested and bedded; and WMB, wet-harvested, bedded, and mole-plowed. Letters adjacent to the numbers in the columns indicate significant differences within columns at the $\alpha = 0.10$ level using Fisher's LSD.

*The results of RCSI and rank change height are identical.

but not RCSB. This was perhaps due to the higher stem densities on the WF treatment (Table 1); however, stocking was not found to be significant as a covariate ($P = 0.949$).

Table 3. Comparison of height, site index, stand biomass, and stem density for combinations of soil disturbance and harvesting residue categories at the polypedon scale (20 m^2) on bedded (B) and nonbedded (NB) sites.

	Height (m)		Site index (m)*		Stand biomass (Mg/ha)		Stem density (trees/ha)	
Disturbance category	NB	B	NB	B	NB	B	NB	B
Minimal								
Class I	10.1a	10.5a	18.7a	19.5a	99b	113a	1570a	1730a
Class II	10.4a	10.6a	19.4a	19.7a	120b	117a	1370b	1800a
Class III	8.7b	11.6a	16.1b	21.5a	81b	135a	1760a	1820a
Moderate								
Class I	10.4a	11.3a	19.4a	20.9a	114b	140a	1850a	1740a
Class II	10.4a	11.2a	19.3a	20.8a	109b	143a	1900a	1780a
Class III	10.2a	11.0a	18.9a	20.4a	104b	131a	1770a	1700a
Heavy								
Class I	9.7b	11.3a	18.0b	21.0a	93b	141a	1730a	1620a
Class II	10.3a	11.0a	19.1a	20.4a	109b	136a	1800a	1700a
Class III	10.2a	9.8a	18.9a	18.3a	117a	115a	1940a	1550b

Note: Disturbance categories were characterized by a mosaic of visible disturbances: minimal, little visible physical disturbance; moderate, primarily compression; heavy, primarily rutting and churning; class I, litter, slash, and slash piles present; class II, litter and slash; and class III, litter without slash. Letters next to the values indicate significant differences within column pairs at the $\alpha = 0.10$ level.

*Base age 25 years.

Height differences between the WF and DF treatments may also be attributed to greater competition on flat-planted sites.

The benefits that bedding and site preparation have for establishing loblolly pine plantations is already well understood (Gent et al. 1983; Miwa et al. 2004; Schultz and Wilhite 1974; Terry and Hughes 1975). First-rotation, mechanically-prepared loblolly pine plantations in their eighth growing season increased wood production by a factor of 1.5 to 3.3 over nonprepared sites in southeast Texas (Stransky et al. 1986). However, the long-term operational impacts of trafficking have remained a question (Reisinger et al. 1988).

Experiments looking at the ability of site preparation to ameliorate badly rutted sites at the operational level are not common. Some later-rotation studies have shown that a decreasing influence of disturbance was detected with age. (Scott and Tiarks 2006) found few significant differences after 18 years of growth between wet- and dry-harvested slash pine (*Pinus elliottii* Engelm.) forests on poorly drained flatwoods in Louisiana. They found that site preparation and fertilization were far more influential on pine production. A study comparing harvesting systems utilizing helicopter logging and skidder traffic on tupelo cypress wetlands showed little difference in terms of hydrology, stand composition, and growth after 16 years of growth despite substantial initial soil impacts (Aust et al. 2006). The presence of shrink swell clays and sediment deposition allowed for natural recovery of soil compaction. In New Zealand, Murphy and Firth (2004) found no significant differences in pine production between heavily disturbed and undisturbed sites on Andisols and moderate topography (50 m relief and 35% slopes).

This study demonstrates that, while dry harvesting is considered desirable, soil and (or) site productivity on wet-harvested sites did not change relative to dry-harvested sites when bedding is employed on wet pine flats. When bedding is not employed, there may be some operational effects on production (Table 2), which may be relevant to nonindustrial private and federal lands where investments in site preparation are less common. The observed changes relative to site index (Table 2) may be due to the effect of wet-weather harvesting disrupting competition on these sites by breaking up root systems (Pritchet and Fisher 1987). On dry-harvested sites where taller noncrop species may be more prevalent, trees must allocate resources to additional height to compete. Alternatively, the disturbances associated with wet-weather harvesting may have improved water retention and survival during some dry years immediately after harvest (Eisenbies et al. 2004).

Polypedon scale

Given that disturbances may only account for a small proportion of an operational treatment, the effect where disturbances may be more intense must still be evaluated. The potential effects of specific disturbances on changes in soil and (or) site productivity are evaluated at the polypedon scale (~0.04 ha). There were few differences detected in height or site index for individual disturbance classes at 10 years of growth with the exception of the minimal–class III and heavy–class I categories (Table 3). Bedding appears to help the problem of bare soil with regards to the minimal–class III category by redistributing and incorporating materials. In the case of the heavy–class I, bedding may help drainage and breakup piles of litter. With regards to biomass, every disturbance combination responded to bedding with the exception of the heavy–class III category (Table 3). These sites were both heavily rutted and had greater than 25% bare soil, and this disturbance combination only occurred on 4% of the wet-harvested sites, and was nonexistent on dry-harvested sites.

The pooled RCSI results indicate that there were no significant changes in soil and (or) site productivity between rotations among the soil physical disturbance classes within each site preparation (Fig. 4); however, the RCSB diagnostic indicated that minimally disturbed, flat-planted sites performed significantly worse relative to the moderately and heavily disturbed areas. Increased soil physical disturbance did not appear to affect changes in soil and (or) site produc-

Fig. 4. Relative change in soil and (or) site productivity based on change in rank in site index (RCSI) and stand biomass (RCSB) for three levels of soil physical disturbance. Different letters indicate Fisher's least significant difference at the α = 0.10 level using prior rank as a covariate.

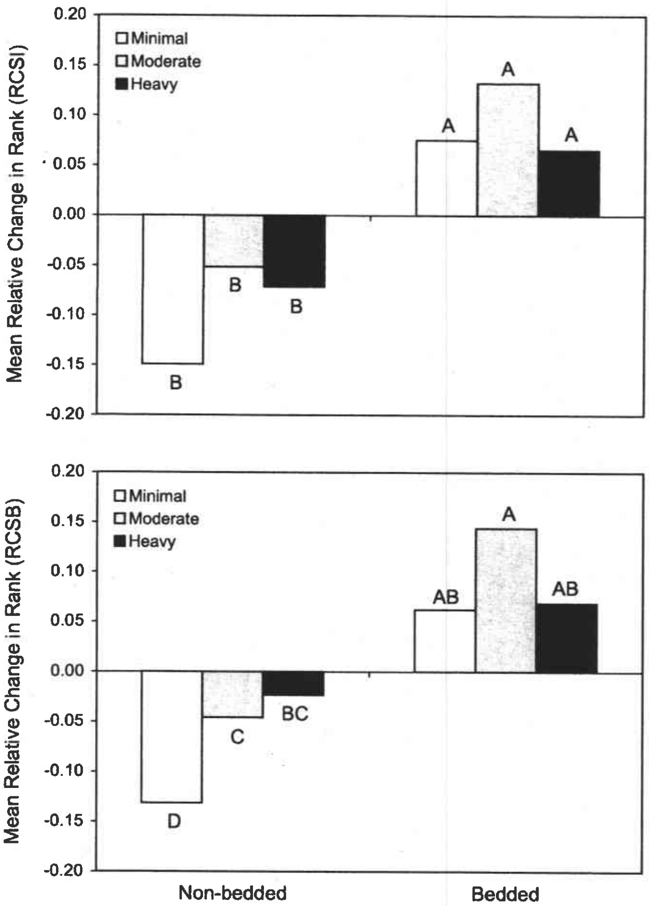
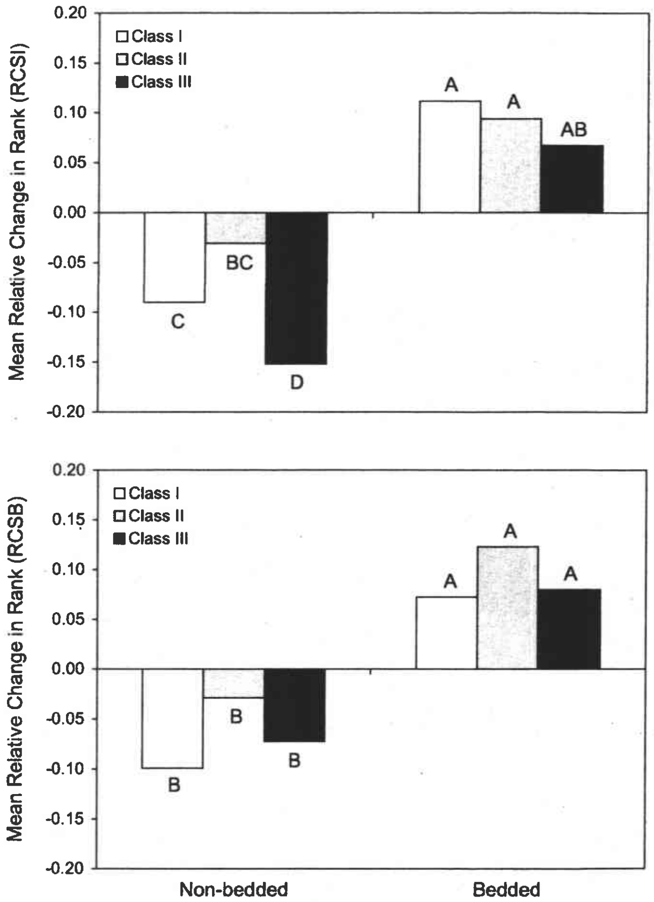


Fig. 5. Relative change in soil and (or) site productivity based on change in rank in site index (RCSI) and stand biomass (RCSB) for three levels of harvesting residue disturbance. Different letters indicate Fisher's least significant difference at the α = 0.10 level using prior rank as a covariate.



tivity when sites were bedded. With regards to harvesting residues, the pooled responses indicate that >25% bare soil is detrimental to maintaining soil and (or) site productivity using the RCSI diagnostic, but this result is not indicated by the RCSB diagnostic (Fig. 5). Although these pooled results are somewhat convoluted, it is clear that when site preparation is employed, the possible effects of compaction, rutting, and churning, and the disturbance and harvesting residues alluded to by these results, are mitigated.

Statistical slicing was utilized to further parse the effects of the individual disturbance classes. The first contrast for the RCSI rank diagnostic evaluated whether bedded sites performed better relative to nonbedded sites with regards to changes in soil and (or) site productivity between rotations. Five disturbance combinations were not significant at the α = 0.1 level: minimal–class I, minimal–class II, moderate–class I, heavy–class II, and heavy–class III (Table 4). Site preparation effects were more prevalent based on the first contrast applied to RCSB (Table 5). Only minimal–class I, minimal–class II, and heavy–class III did not respond to bedding. Nonsignificant responses are either due to sites not responding to site preparation or a lack of initial site impact. Morris and Lowery (1988) illustrate how many site preparations may have limited potential for permanently improving soil quality. Compaction and anaerobic conditions can limit the depth and extent of root systems by reducing aeration and hydraulic conductivity (Gent et al. 1983; Gilman et al. 1987). Roots become impeded between 1.4 and 1.6 g/cm^3 (Tuttle et al. 1988). However, given the operational results, sites obviously do respond to site preparation, but there is no clear gradient with regards to site disturbances.

The second and third contrast compared each disturbance category with an "ideal" condition as a reference. The minimal–class II is considered ideal because it was characterized by little observable soil disturbance and had sufficient organic residues (~7 kg/m^2). With regards to RCSI, only the minimal–class III disturbance category was significantly different from the reference category, performing better on the bedded sites and worse on the nonbedded sites (Table 3). Again, with such a small percentage representing this class it is hard to explain these observations. Meanwhile, there were no categories that were significantly different than the reference with regards to RCSB (Table 4). It appears that there is no consistent gradient with regards to specific disturbance categories after 10 years of growth. Despite negative impacts on growth after 2 years on skid trails,

Table 4. Relative change in soil and (or) site productivity between rotations for combinations of soil physical disturbance, harvesting residue, and site preparation based on the change in rank of the site index (RCSI).

	RCSB		P		
Disturbance category	Nonbedded	Bedded	Contrast 1*	Contrast 2†	Contrast 3‡
Minimal					
Class I	–0.117	0.011	0.216	0.951	0.273
Class II	–0.003	0.017	0.898	Reference	Reference
Class III	–0.329	0.198	<0.001	0.090	0.011
Moderate					
Class I	–0.004	0.147	0.148	0.217	0.988
Class II	–0.070	0.157	0.033	0.177	0.521
Class III	–0.081	0.094	0.095	0.453	0.441
Heavy					
Class I	–0.149	0.178	0.003	0.126	0.161
Class II	–0.022	0.108	0.213	0.382	0.863
Class III	–0.045	–0.089	0.704	0.313	0.717

Note: Disturbance categories were characterized by a mosaic of visible disturbances: minimal, little visible physical disturbance; moderate, primarily compression; heavy, primarily rutting and churning; class I, litter, slash, and slash piles present; class II, litter and slash; and class III, litter without slash.

*Contrast 1: significant response to bedding.

†Contrast 2: significantly different from the bedded, minimal–class II reference (ideal).

‡Contrast 3: significantly different from flat-planted, minimal–class II reference (ideal).

Table 5. Relative change in soil and (or) site productivity between rotations for combinations of soil physical disturbance, harvesting residue, and site preparation based on the change in rank of stand biomass (RCSB).

	RCSB		P		
Disturbance category	Nonbedded	Bedded	Contrast 1*	Contrast 2†	Contrast 3‡
Minimal					
Class I	–0.154	–0.044	0.245	0.370	0.234
Class II	–0.042	0.040	0.379	Reference	Reference
Class III	–0.198	0.192	0.001	0.107	0.141
Moderate					
Class I	–0.032	0.143	0.065	0.271	0.916
Class II	–0.006	0.198	0.035	0.101	0.698
Class III	–0.099	0.092	0.051	0.574	0.552
Heavy					
Class I	–0.111	0.118	0.020	0.401	0.460
Class II	–0.038	0.132	0.072	0.321	0.964
Class III	0.079	–0.044	0.240	0.372	0.250

Note: Disturbance categories were characterized by a mosaic of visible disturbances: minimal, little visible physical disturbance; moderate, primarily compression; heavy, primarily rutting and churning; class I, litter, slash, and slash piles present; class II, litter and slash; and class III litter without slash.

*Contrast 1: significant response to bedding.

†Contrast 2: significantly different from the bedded, minimal–class II reference (ideal).

‡Contrast 3: significantly different from flat-planted, minimal–class II reference (ideal).

productivity was restored after 4 years of growth on wet pine flats in South Carolina (Aust et al. 1998*b*). Site factors that affect growth at one point in a rotation may not be the same as another (Eisenbies et al. 2006; Kelting et al. 1999); site productivity may be a dynamic site attribute throughout stand development, making generalizations quite difficult.

Soil resilience and recovery

Dry-weather harvesting resulted in minimal changes to bulk density (Table 6). As with studies throughout the southeastern United States (Reisinger et al. 1988), wet-weather harvesting caused soil bulk density to increase immediately after harvesting by up to 0.24 g/cm^3 (20%) in the diagnostic A horizon, and appeared to maximize 2 years (1.44 g/cm^3) after planting. Soil bulk densities increased up to 0.25 g/cm^3 for all physical disturbance categories (Table 7). Moderate and heavy disturbance classes still had significantly higher soil bulk densities (and lower porosities) than minimally disturbed sites. The drum chopping (bedded and nonbedded sites) is probably the cause of the increase between the post-harvest and 2 year measurements; however, it is also clear that bedding and time helps remediate such disturbances on these sites. On coastal plain and piedmont soils, bedding and disking effectively restore soil physical properties in the

Table 6. Key soil physical properties associated with wet- and dry weather harvesting on bedded and flat-planted sites at four time steps.

Treatment	Preharvest*	Postharvest*	Age (years) 2[†]	7
Bulk density (g/cm³)[‡]				
Nonbedded				
Dry harvested	1.16a	1.18b	1.42	1.23a
Wet harvested	1.16a	1.39a	1.44	1.23a
Bedded				
Dry harvested	1.13a	1.15b	1.19	1.10a
Wet harvested	1.14a	1.38a	1.17	1.28a
Saturated hydraulic conductivity (cm/h)[‡]				
Nonbedded				
Dry harvested	15a	14a	12	4.5a
Wet harvested	19a	4.3b	9.5	9.1a
Bedded				
Dry harvested	6.5a	6.2b	19	24a
Wet harvested	9.2a	3.1b	24	13a
Total pore space (%)[‡]				
Nonbedded				
Dry harvested	54a	54a	48	53a
Wet harvested	55a	49b	48	54a
Bedded				
Dry harvested	55a	55a	58	59a
Wet harvested	54a	50b	58	52a
Macropores (%)[‡]				
Nonbedded				
Dry harvested	14a	14a	11	14a
Wet harvested	17a	8.9b	9.5	14a
Bedded				
Dry harvested	12a	12ab	11	13a
Wet harvested	16a	10ab	12	15a

Note: Letters next to the values indicate significant differences within columns only.
*Pre- and post-harvest values were reported in Xu et al. (2002).
[†]Data for the 2 year step were interpolated from Lister et al. (2004) and weighted by percent coverage as reported by Eisenbies et al. (2005).
[‡]Least-squares means.

upper 30 cm outside of skid trails (Gent et al. 1983). The recovery of these sites over time is attributed to the presence of 2:1 shrink swell clays that help these soils to recover as they wet and dry over many seasons.

Corresponding to changes in bulk density, total porosity also decreased and recovered. No significant change in macropore space was observed. Saturated hydraulic conductivity in the diagnostic A horizon was marginally diminished. Oxidation depth (steel rods) measured at 7 years of growth indicated the soils were well-aerated to the argillic horizon and no significant differences between treatments were found.

It is perhaps a surprising, if not counterintuitive, result that disturbances induced by wet-weather harvesting do not permanently degrade and may even enhance soil and (or) site productivity. Harvesting disturbance certainly can degrade sites. For instance, trafficking resulted in increased bare soil and rutting, decreased height growth, and survival after 2 years of growth in quaking aspen (*Populus tremuloides* Michx.) forests (Bates et al. 1993). However, not all sites will necessarily be sensitive to harvesting disturbances. While loblolly pine seedlings have difficulty establishing on soils receiving >3.5–7 kg/cm² static pressure, mechanical loosening also increased seedling growth on clayey soils (Foil and Ralston 1967). The effect of increased soil bulk density on root growth varies with soil texture (Daddow and Warrington 1983).

Wet pine flats may simply be resilient to disturbance associated with loblolly pine production and benefit from the natural capacity of these soils to recover from physical disturbances. Soil physical disturbance and bedding may increase soil water retention in drought by altering porosity (Powers 1999) (Tables 6 and 7) or by increasing nitrogen mineralization rates by the Assart effect (Table 8) (Li et al. 2003). On these sites, the low hydraulic conductivities of the argillic horizon prevent it from becoming saturated, therefore, it maintains its strength even though logging equipment may heavily impact the surface horizons. Additionally, on heavily disturbed areas planters preferentially located seedlings on the high points between ruts that served as "pseudobeds", which can enhance surface drainage if they are well connected (Eisenbies et al. 2005). The churned disturbance type usually did not result in increased soil bulk

Table 7. Key soil physical properties associated with soil physical disturbances on bedded and flat-planted sites at four time steps.

Disturbance category	Preharvest*	Postharvest†	Age (years) 2‡	Age (years) 7
Bulk density (g/cm^3)§				
Nonbedded				
Minimal	1.17	1.25	1.42	1.14b
Moderate		1.31	1.43	1.31a
Heavy		1.42	1.44	1.20ab
Bedded				
Minimal	1.17	1.25	1.20	1.07b
Moderate		1.31	1.18	1.14b
Heavy		1.42	1.17	1.33a
Saturated hydraulic conductivity (cm/h)§				
Nonbedded				
Minimal	13	9.5	13	5.5a
Moderate		7.1	11	41a
Heavy		2.5	8.0	11a
Bedded				
Minimal	13	9.5	17	26a
Moderate		7.1	22	48a
Heavy		2.5	26	7.2a
Total pore space (%)§				
Nonbedded				
Minimal	53	51	48	57a
Moderate		50	48	51b
Heavy		49	48	55ab
Bedded				
Minimal	53	51	58	60a
Moderate		50	58	57a
Heavy		49	58	50b
Macropores (%)				
Nonbedded				
Minimal	14	14	11	12a
Moderate		12	10	13a
Heavy		8	9.0	15a
Bedded				
Minimal	14	14	11	16a
Moderate		12	12	20a
Heavy		8	12	18a

Note: Disturbance categories were characterized by a mosaic of visible disturbances: minimal, little visible physical disturbance; moderate, primarily compression; and heavy, primarily rutting and churning. Letters after the values in the table indicate significant differences within column only.

*Data from Burger (1994).

†Postharvest values were interpolated from Aust et al. (1998*a*) and weighted by percent coverage as reported by Eisenbies et al. (2005).

‡Data from the 2 year step were interpolated from Lister et al. (2004) based on percent coverage as reported by Eisenbies et al. (2005).

§Least-squares means.

densities (Aust et al. 1998*a*). Also, heavy disturbance can enhance competition control by breaking up root systems (Pritchet and Fisher 1987). The reduced performance observed on the minimally disturbed, nonbedded sites (Fig. 4) may be related to the amount of harvesting debris (Fig. 5). Dry-harvested areas tended to be less physically disturbed, but had less harvesting residues left on the site because of the raking effect of skidding trees (Eisenbies et al. 2005).

Other studies have also shown no negative effects from similar trafficking disturbances. On wet pine flats in South Carolina, no decrease in productivity was observed after 2 years of growth owing to site preparation on trafficked sites (Aust et al. 1998*b*). Reisinger et al. (1994) observed that wet-weather compaction of a sandy loam during a mechanized thinning operation of a natural loblolly pine stand was not detrimental to tree growth, and that mild rut-

Table 8. Net nitrogen mineralization rates at ages 2 and 7 for three levels of soil physical disturbance and two levels of site preparation.

	Net nitrogen mineralization (kg/ha/year)*	
Disturbance category	At 2 years†	At 7 years
Nonbedded		
Minimal	47	16b
Moderate	52	16b
Heavy	68	19b
Bedded		
Minimal	109	49a
Moderate	88	43a
Heavy	62	39a

Note: Disturbance categories were characterized by a mosaic of visible disturbances: minimal, little visible physical disturbance; moderate, primarily compression); and heavy, primarily rutting and churning.

*Least-squares means.

†Data from the 2 year step were interpolated from Lister et al. (2004) and weighted by percent coverage as reported by Eisenbies et al. (2005).

ting (<6 in., 1 in. = 25.4 mm) disturbances may be beneficial. Ruts caused by skidder traffic facilitated growth of more flood-tolerant species in tupelo–cypress stands (Aust et al. 2006). Harvesting disturbance also facilitated sediment accumulations of 10–20 cm greater than control plots after 16 years of growth. Miller et al. (1996) did not detect differences in the growth of four major tree species after compaction (with and without tillage) of fine textured soils in the Pacific Northwest, although survival of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) may have been affected on nontilled sites.

Other considerations

There appears to be a minor discrepancy between the operational- and polypedon-scale results. At the operational scale, the wet-harvested, flat-planted sites were the poorest performers; however, at the polypedon scale, sites with moderate to heavy disturbance were equal or better than minimally disturbed sites. The statistical significance was sometimes detected and sometimes not detected. There may be disturbance factors that are not accounted for by visual means or that our disturbance factors were not sampled with the same intensity as the trees. Our study lacks the power required to test such a question. Changes in soil and (or) site productivity were related to initial site productivity, site preparation, relative elevation, distance to landing, and soil type, all of which reflect local drainage (Eisenbies et al. 2006). What may be an obvious, yet salient fact, is that loblolly pine is an early successional species that thrives on disturbed sites. Loblolly pine can still be sensitive to individual soil disturbances and competition, which can greatly affect crown differentiation (Baker and Langdon 1990). At 10 years of growth, there was still a wide degree of variability in the stages of stand development ranging between the beginning of full stand closure initiation, stem exclusion, and some areas beginning to develop understory components.

Conclusions

It is well-documented that bedding is an effective silvicultural operation on wet sites, but this study also indicates that bedding can be an effective amelioration technique for disturbed sites. This study illustrates that wet-weather harvesting does not appear to affect the relative productivity of sites at the operational scale when sites are bedded. Until the end of this rotation, it is not possible to put full weight on the results of this study; however, at 10 years of growth there is evidence that when site preparation is employed wet-weather harvesting is not detrimental to soil and (or) site productivity at the operational scale. Because of several dry years immediately after planting, survival was excellent. Because of the comparatively high costs of operating heavy machinery, flat planting may be more economically viable, especially if interest rates rise (data not shown); however, site preparation may remain the best choice to ensure proper stocking. If conditions had been wetter these results may have been different, which may be of particular importance to nonindustrial and federal forest managers where intensive site preparation is not commonly employed.

Based on results at the polypedon scale, some level of harvesting disturbance may enhance growth. On flat-planted sites, there is some evidence that wet-weather harvesting may be detrimental to soil and (or) site productivity; however, trends in the rank diagnostic suggest differences may no longer exist by the end of the rotation. On the flat-planted sites at the polypedon scale there has been some divergence in the rank-change response within the soil physical disturbance and harvesting residue classes from 5 years of growth onwards. Given that these soils continue to recover with regards to soil physical properties because of their mixed mineralogy and seasonal wetting and drying, it is uncertain whether these responses will remain until the end of the ~20 year rotation. This result indicates that one-time and short-duration measurements of soil properties may not be sufficient for monitoring disturbance effects on long-term productivity.

Regulations that limit harvesting traffic or soil physical disturbance must also consider the resistance and resilience of specific site types, as well as the ameliorative effects of site preparation. More research is required to identify resistant and resilient sites where wet-weather harvesting may be conducted to protect sites that may be sensitive to trafficking during wet weather.

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