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Soil properties in site prepared loblolly pine (*Pinus taeda* L.) stands 25 years after wet weather harvesting in the lower Atlantic coastal plain

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A B S T R A C T

Harvesting traffic may alter soil properties and reduce forest productivity if soil disturbances are not mitigated. Logging operations were conducted during high soil moisture conditions on the South Carolina, USA coast to salvage timber and reduce wildfire potential following Hurricane Hugo in 1989. Long term study sites were established on wet pine flats to evaluate effects of primary skid trails and site preparation on soil properties and loblolly pine productivity. The experiment was analyzed as a split-plot within an unbalanced randomized complete block design having 12 blocks, two levels of traffic (primary skid trail (On), no obvious traffic (Off)) and four levels of site preparation (bedding (Bed), disking with bedding (D/B), disking (Disk), no site preparation (None)). Remeasurement of the study was conducted in 2015 at 25 years after salvage logging (stand age 23 years). Bed and D/B treatments had greater saturated hydraulic conductivity ($p = 0.0567$) and macroporosity ($p = 0.0071$) and lower bulk density ($p = 0.0226$) values than Disk and None treatments. Macroporosity benefits were evident two years after site preparation installation, but bulk density and saturated hydraulic conductivity were not, suggesting these two measurements were affected over time by differences in rooting activity influenced by initial aeration benefits. Depth to iron depletion ($p = 0.0055$) was significantly greater and soil carbon ($p < 0.0001$) was significantly lower in Bed and D/B treatments due to bed elevation above the water table and improved drainage. This implies greater aeration for roots, but trade-offs in aboveground biomass and soil carbon storage. However, above and below ground carbon differences balanced one another between treatments so that combined carbon storage in soil and above ground loblolly pine biomass was not significantly different by site preparation treatment ($p = 0.1127$). Bed and D/B resulted in approximately double the stand biomass ($p < 0.0001$) and stand density ($p < 0.0001$) than Disk and None. Bed and D/B generally created more favorable soil properties and enhanced long term loblolly pine stand productivity. Differences in soil properties and stand productivity between traffic levels, with and without site preparation, were negligible suggesting natural soil recovery mechanisms were mitigated effects of wet site harvesting over 25 years.

1. Introduction

1.1. Background

Society benefits from numerous ecosystem services provided by forests. Demands for these services are expected to increase concomitantly with global declines in forested land area due to human population growth (Burger, 2009; FAO, 2015; Fox, 2000). To capitalize on timber resources, forests are often harvested with heavy machinery which has potential to alter soil properties, thereby reducing forest productivity and quality of ecosystem services (Cambi et al., 2015; Miwa et al., 2004). The effects of heavy equipment traffic on soil properties and forest productivity have been investigated around the world (Horn et al., 2004; Makineci et al., 2007; Murphy et al., 2004; Naghdi et al., 2016; Pinard et al., 2000; Powers et al., 2005; Rab, 2004). Forest harvest related soil disturbances that have been associated with decreased forest productivity include compaction (Greacen and Sands, 1980; Moehring and Rawls, 1970), decreased saturated hydraulic

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Fig. 1. Approximate location of study area within the Francis Marion National Forest, Berkeley County, S.C., United States.

conductivity (Gent et al., 1984, 1983), poor aeration (Aust et al., 1998a, 1995, 1993; Xu et al., 2002), reduced nutrient availability (Powers et al., 2005; Tan et al., 2005), increased mechanical resistance to root penetration (Carter et al., 2007; Hatchell et al., 1970; Lockaby and Vidrine, 1984), and organic matter displacement (Powers et al., 2005; Rab, 2004).

In the Southeastern U.S. coastal plain, intensively managed pine plantations are commonly implemented to enhance timber production and the quality of ecosystem services on a per hectare basis (Fox, 2000; Stanturf et al., 2003). Pine plantations may occur on "wet pine flats," "wet flats," or "wet flatwoods," and some satisfy criteria of jurisdictional wetlands (Harms et al., 1998). In addition to those provided by upland forests, forested wetlands provide a suite of ecosystem services that may be jeopardized by traditional forestry practices (Richardson, 1994). The frequent high soil moisture conditions characteristic of wetlands may exacerbate degradation of soil properties caused by equipment traffic (Akram and Kemper, 1979; Cambi et al., 2015; Greacen and Sands, 1980; Miwa et al., 2004; Moehring and Rawls, 1970). Forestry best management practices recommend avoidance of equipment operation during periods of high soil moisture, but this is often not logistically or economically feasible (Miwa et al., 2004). The resulting changes in soil properties must be mitigated to a condition capable of supporting desired species, either naturally or artificially, to ensure forestry is sustainable (Burger, 2009; Fox, 2000). Some forests apparently have adequate natural soil and productivity recovery mechanisms such as sediment deposition (McKee et al., 2012), shrink-swell activity (Lang et al., 2016, McKee et al., 2012), weather patterns (Eisenbies et al., 2007; Passauer et al., 2013), and resilience to compaction (Powers et al., 2005).

Site preparation can enhance forest productivity by manipulating soil properties (Fox, 2000; Morris and Lowery, 1988). Researchers have also suggested that site preparation is essential to ameliorate properties and productivity of soils disturbed by logging (Lof et al., 2012; Miwa et al., 2004; Reisinger et al., 1988). Bedding and disking have traditionally been prescribed in the Southeastern U.S. to augment or mitigate soil properties and site productivity, and short term benefits of bedding and variable results of disking have been reported (Aust et al., 1998b; Gent et al., 1984, 1983; Hatchell, 1981; Mann and Derr, 1970; McKee and Shoulders, 1974; Pritchett, 1979; Xu et al., 2002). Long term effects of bedding on forest productivity are also widely reported (Gent et al., 1986; McKee and Hatchell, 1986; McKee and Wilhite, 1986; Passauer et al., 2013; Tiarks and Haywood, 1996; Wilhite and Jones, 1981); however; few studies report the long term effects of mechanical site preparation on soil properties (Kyle et al., 2005; Lang et al., 2016). Evaluating how soil properties change over time allows for understanding of factors controlling forest productivity such that management prescriptions can be made precisely, efficiently, and sustainably to fulfill the growing demand for forest ecosystem services (Burger, 2009).

1.2. Objectives

The objectives of this study are to evaluate the effects of site preparation and wet weather primary skid trails on selected soil properties and stand productivity at stand age 23 years (25 years after salvage logging). The study also seeks to determine if soil properties and stand productivity in non-site prepared primary skid trails have naturally recovered to the state of an undisturbed soil at stand age 23 years. The effects of these treatments on loblolly pine productivity are presented in Neaves et al. (2017).

2. Methods

2.1. Study site description

Six experimental sites were established within the Francis Marion National Forest in Berkeley County, South Carolina, United States (Fig. 1). Berkeley County is in the lower Atlantic coastal plain physiographic region. Average annual precipitation is 129 cm (NOAA, 2016), and average daily high temperatures are near or above 32 °C during the summer and 15.5 °C in the winter (Long, 1980). The sites were established in 1989 to study the long term effects of site preparation and wet weather primary skid trails on soil properties and loblolly pine productivity. The study was implemented following the salvage logging of timber damaged by Hurricane Hugo. Five to twelve loblolly or longleaf pine trees per hectare remained standing after the hurricane (Scheerer, 1994; Tippett, 1992).

The sites are characterized as wet pine flats, distinguished by minimal lateral relief, dense argillic horizons, and longleaf pine (*Pinus palustris* Mill.) and loblolly pine (*Pinus taeda* L.) dominated canopies. Dominant soil series within the study sites include somewhat poorly drained Lynchburg (fine-loamy, siliceous, semiactive, thermic Aeric

Paleaquults), moderately well drained Goldsboro (fine-loamy, siliceous, subactive, thermic Aquic Paleudults), poorly drained Rains (fine-loamy, siliceous, semiactive, thermic Typic Paleaquults), somewhat poorly drained Wahee (fine, mixed, semiactive, thermic Aeric Endoaquults), and poorly drained Bethera (fine, mixed, semiactive, thermic Typic Paleaquults) (USDA NRCS, 2016a, 2016b). Each of these soils has a water table at or near the soil surface during some part of the year.

2.2. Experimental design

The study was conducted as a split plot within an unbalanced randomized complete block design with 12 blocks. The blocking allowed soil series and drainage classes to be grouped. Two levels of traffic provided the main factor (primary skid trail, no obvious disturbance) and four levels of site preparation provided the subfactor plot factor (bedding, flat disking, flat disking with bedding, and no site preparation), and with a total of 94 subplot experimental units. Two of the original 96 subplot experimental units, established 23 years earlier, could not be re-located for measurement in this study, resulting in the slightly unbalanced design.

2.3. Treatments

During the fall and winter of 1989, each of the six experimental sites were salvage logged with rubber tired skidders during high soil moisture conditions which caused obvious compaction and rutting (Tippett, 1992). The site preparation treatments were bedding (Bed), flat disking with bedding (D/B), flat disking (Disk), and no site preparation (None). Prior to site preparation installation, debris was removed using a Komatsu 65D bulldozer. Flat disk treatments were installed using a John Deere 400 bulldozer, and bed treatments were implemented with a Komatsu 65D bulldozer and fire plow. Site preparation installation was completed in September 1991. Each site preparation treatment was implemented on a primary skid trail (On) and in an area that was not obviously disturbed (Off) (Fig. 2). Experimental unit subplots are each 24.4 × 6.1 m in size (Tippett, 1992). Detailed maps of subplot units within each site are provided in Tippett (1992). Loblolly pine seedlings from a local nursery were planted on a 2.0 × 0.6 m spacing (three rows in each subplot) in February 1992 and thinned to approximately a 2.0 × 1.8 m spacing in 1996 (Scheerer, 1994). The thinning at stand age 4 years was conducted to reduce the artificially high planting density by removing 2 out of every 3 trees. Treatment combinations of the two unmeasured experimental units are On-Disk and Off-Disk.

2.4. Data collection

All field data collection occurred during the summer of 2015, with the exception of approximately 130 soil cores which were compromised. Replacement cores were collected during June 2016. Eight 2.5 × 5 cm soil cores were systematically collected from the soil surface in each subplot experimental unit (Fig. 3) using a hammer driven double core soil sampler and sealed for later analysis of saturated hydraulic conductivity (Ksat) (Klute and Dirksen, 1986), pore size distribution (Danielson and Sutherland, 1986), and bulk density (Blake and Hartge, 1986). For bulk density calculation, woody material in the core was weighed, discarded, and the volume of mineral soil was correcting assuming an oven dry organic matter density of 0.8 g/cm^{-3}. No rocks were encountered during sampling. Composite subsamples were systematically collected from the upper 15 cm of the soil profile using a push tube sampler (Fig. 3) (Petersen and Calvin, 1986). These samples were air dried, ground, passed through a two mm sieve and partitioned for analysis of carbon, nitrogen, and phosphorus. Total soil carbon and total nitrogen concentrations were determined from this material using a carbon and nitrogen analyzer (Elementar, Inc. Vario Max CNS). Phosphorus was extracted using a Melich-1 double acid extract solution and concentration determined using ICP-OES (Varian, Inc. Vista-MPX CCD Simultaneous ICP-OES). Phosphorus mass per hectare to a soil depth of 15 cm was calculated using average bulk density for each subplot. Two soil profile descriptions were performed in each experimental unit to designate horizons and determine minimum soil depth to common, distinct (or greater quantity and contrast) iron depletions (Schoeneberger et al., 2012). A relative comparison of soil penetration resistance was attained using a Durham Geo Slope Indicator S-205 dynamic cone penetrometer. The 6.80 kg driving anvil was dropped from a height of 50.8 cm 20 times, and the total depth of penetration

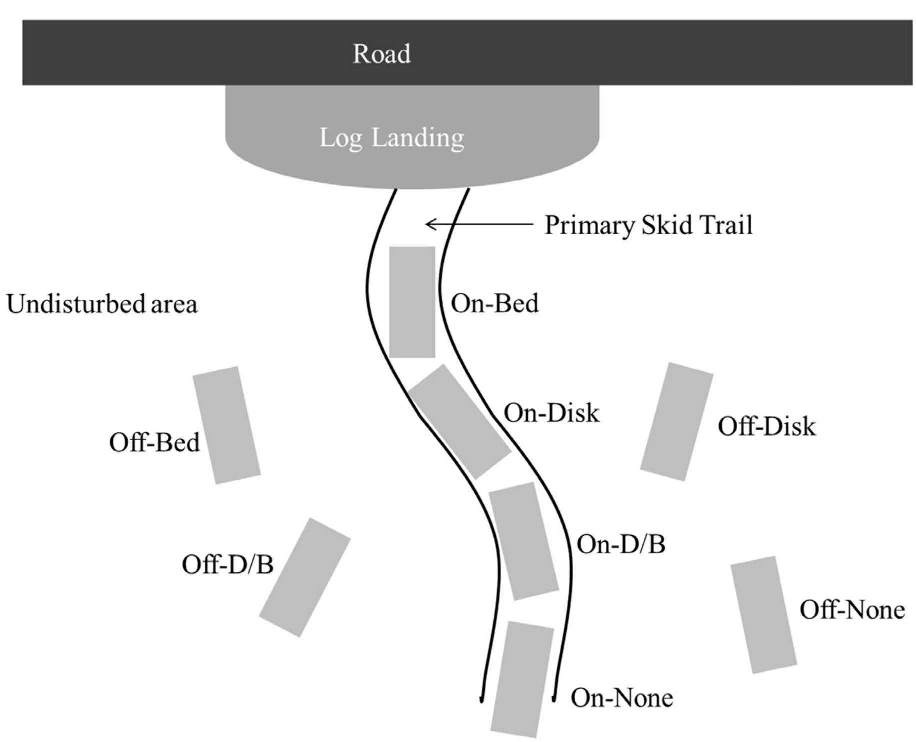

Fig. 2. Generalized layout of treatment subplots within a block.

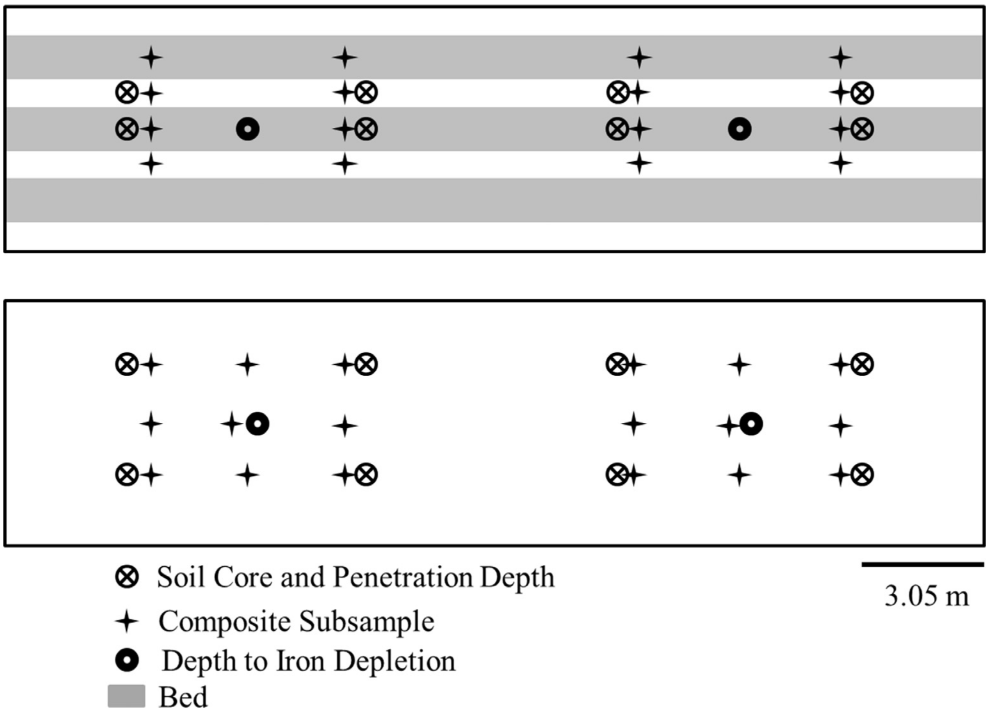

Fig. 3. Schematic of systematic subsampling with Bed and D/B treatment subplots (top) and Disk and None subplots (bottom).

below the soil surface was recorded. Total heights and diameters at breast height (DBH) of all living loblolly pine trees in each subplot were measured. Total dry above ground biomasses of individual trees were calculated using an allometric equation provided by Gonzalez-Benecke et al. (2014). Green weights were approximated by multiplying the result of this equation by a factor of two. Stand density and aboveground biomass per hectare were calculated by scaling the number of trees and total biomass in each subplot, respectively, to one hectare. Carbon stored in above ground loblolly pine biomass was approximated by multiplying the dry above ground loblolly pine biomass in each subplot by 0.5. Mass of carbon stored in the upper 15 cm of soil in each subplot was estimated based on the measured soil carbon percentage and bulk density. Results were scaled to one hectare and added to the estimate of carbon stored in above ground loblolly pine biomass per hectare to yield an estimate of stand carbon storage (soil + loblolly pine carbon), excluding roots and all other vegetation. Subsamples for all soil measurements were obtained systematically as shown in Fig. 2 to avoid the edge of subplots and to account for potential systematic variability between halves of each subplot. The experiment was originally designed as a split-split plot with two levels of fertilization; however we were unable to determine the sub-subplot units to which this treatment was applied so values from each sub-subplot were pooled. See Scheerer (1994) and Aust et al. (1998b) for additional details on original experimental design.

2.5. Statistical analysis

The main effects of site preparation were analyzed using standard two-way ANOVA procedures for all measurements. The main effects of traffic were analyzed using standard two-way ANOVA procedures for all measurements except depth to iron depletion and total porosity. Significant treatment interaction for these to measurements obscured the effect of traffic so they were analyzed using a one-way ANOVA with eight different treatment combinations (i.e. Off-None, On-Disk). All measurements for the Off-None and On-None treatments were compared using a contrast in a one-way ANOVA. An appropriate transformation was performed on all responses exhibiting nonparametric behavior. All multiple means separations were conducted using Fisher's LSD at $\alpha = 0.1$ (Ott and Longnecker, 2010; Stefano, 2001). Analysis procedures were performed using JMP Pro 13 statistical software (SAS Institute, Inc., 2016).

3. Results

3.1. Interaction

The interaction of block and site preparation was significant for macroporosity ($p = 0.0371$), microporosity ($p < 0.0001$), total porosity (0.0214), penetration depth ($p < 0.0001$), depth to iron reduction ($p = 0.0281$), total soil nitrogen ($p < 0.0001$), soil carbon ($p < 0.0001$), stand biomass ($p = 0.0004$), and stand density ($p = 0.0002$). These interactions were co-directional, as indicated by interaction plots. Block and site preparation did not interact significantly for bulk density, Ksat, soil phosphorus, and soil + loblolly pine carbon.

The interaction of site preparation and traffic was significant for total porosity ($p = 0.0484$) and soil depth to iron depletion ($p = 0.0132$). Interaction plots indicated that the effects of site preparation obscure the effects of traffic so these responses were analyzed as eight separate treatment combinations to examine the effect of traffic. Treatment interaction was not significant for all other measurements.

3.2. Site preparation

The Disk and None site preparation treatments were not significantly different from one another for any of the evaluated soil physical parameters (Table 1). Site preparation significantly affected bulk density ($p = 0.0226$). D/B had significantly lower bulk density than Disk and None, but not Bed. Bulk density of Bed was significantly less than Disk, but was not significantly different from None. Ksat ($p = 0.0567$) and macroporosity ($p = 0.0071$) were significantly greater for Bed and D/B than Disk and None, but Bed and D/B were not significantly different from each other. Site preparation did not significantly affect microporosity ($p = 0.1461$). D/B had the greatest total porosity ($p = 0.0207$), which was significantly greater than Disk and

Table 1
LS mean values for soil physical properties by site preparation treatment. Values not followed by the same letter within a column are significantly different using Fisher's LSD at α = 0.1.

Site preparation	Bulk density (S.E.) (Mg m^{-3})	Ksat (S.E.) (cm h^{-1})	Macroporosity (S.E.) (%)	Microporosity (S.E.) (%)	Total porosity (S.E.) (%)	Penetration depth (S.E.) (cm)
Bed	1.39 bc (0.02)	34.76 a (4.41)	11.42 a (0.44)	35.35 a (0.60)	46.77 ab (0.66)	32.70 a (1.02)
D/B	1.36 c (0.02)	23.77 a (4.41)	10.89 a (0.44)	36.79 a (0.60)	47.68 a (0.66)	34.22 a (1.02)
Disk	1.43 a (0.02)	13.80 b (4.71)	9.27 b (0.46)	35.77 a (0.64)	44.64 c (0.69)	29.27 b (1.10)
None	1.42 ab (0.02)	11.92 b (4.60)	8.27 b (0.45)	36.70 a (0.63)	45.68 bc (0.69)	28.42 b (1.07)

None, but not Bed. Bed had significantly greater total porosity than Disk, but not None. The effect of site preparation on penetration depth was significant ($p = 0.0009$). Bed and D/B had significantly greater penetration depth than Disk and None, but were not significantly different from each other (Table 1).

Disk had significantly greater soil phosphorus ($p = 0.0002$) than all other treatments. None had significantly greater soil phosphorus than D/B, but was not significantly different than Bed. Bed and D/B do not have significantly different soil phosphorus values. Site preparation significantly affected total soil nitrogen ($p < 0.0001$) and soil carbon ($p < 0.0001$). Nitrogen and carbon were significantly lower in Bed and D/B than Disk and None, but bed and D/B were not significantly different from each other. None and Disk were also not significantly different in terms of total soil nitrogen and soil carbon. Bed and D/B had significantly greater soil depth to common, distinct iron depletion ($p = 0.0055$) than Disk and None, but did not differ significantly from each other. Disk and None also do not have significantly different soil depth to iron depletion (Table 2). Bed and D/B have significantly greater stand biomass ($p < 0.0001$) and stand density ($p < 0.0001$) than Disk and None, but Bed and D/B are not significantly different from each other. None and Disk are also not significantly different in terms of stand biomass and stand density. Soil + loblolly pine carbon storage does not differ significantly by site preparation treatment ($p = 0.1127$) (Table 3).

3.3. Traffic

After 23 years, Traffic did not significantly affect Ksat ($p = 0.6144$), Macroporosity ($p = 0.9285$), or microporosity ($p = 0.9943$). Bulk density was significantly higher in primary skid trails than in relatively undisturbed soils ($p = 0.0862$). Penetration depth was significantly greater for Off than On (Table 4). Traffic had no significant effect on soil phosphorus ($p = 0.1340$), total soil nitrogen ($p = 0.2589$), of soil carbon ($p = 0.2698$) (Table 5). Stand biomass ($p = 0.1564$), stand density ($p = 0.4662$), and soil + loblolly pine carbon ($p = 0.1105$) were also not significantly affected by traffic level (Table 6) Due to significant treatment interactions of traffic and site preparation for soil depth to iron depletion and total porosity, effects of traffic were considered within the same site preparation treatment for these measurements. Off-Bed had significantly lesser depth to iron depletion than On-Bed, but traffic did not have a significant effect on depth to iron depletion within any other levels of site preparation (Table 7). Total porosity was significantly greater for Off-Bed than On-Bed, but did not differ significantly by traffic level within any other levels of site preparation (Table 7).

Table 2
LS mean values for soil chemical properties by site preparation treatment. Values not followed by the same letter within a column are significantly different using Fisher's LSD at α = 0.1.

Site preparation	Phosphorus (S.E.) (kg ha^{-1})	Total nitrogen (S.E.) (μg g^{-1})	Carbon (S.E.) (Mg ha^{-1} to 15 cm)	Soil depth to iron depletion (S.E.) (cm)
Bed	2.43 bc (0.12)	753.87 a (50.94)	45.2 a (2.71)	39.95 a (2.56)
D/B	2.18 c (0.12)	765.80 a (50.94)	44.6 a (2.65)	38.79 a (2.56)
Disk	3.02 a (0.13)	1050.51 b (55.02)	63.0 b (3.00)	30.37 b (2.77)
None	2.66 b (0.12)	1062.84 b (50.94)	66.8 b (2.76)	28.47 b (2.56)

Table 3
LS mean values stand level parameters by site preparation treatment. Values not followed by the same letter within a column are significantly different using Fisher's LSD at α = 0.1.

Site preparation	Stand biomass green weight (S.E.) (Mg ha^{-1})	Stand density (S.E.) (No. Trees ha^{-1})	Soil + loblolly pine carbon (S.E.) (Mg ha^{-1})
Bed	265.8 a (20.91)	1082.0 a (107.37)	111.5 a (5.44)
D/B	243.2 a (20.91)	1025.9 a (107.37)	105.3 a (5.44)
Disk	129.8 b (22.59)	516.8 b (115.79)	95.3 a (5.87)
None	112.8 b (20.91)	448.5 b (107.37)	94.8 a (5.44)

Table 4
LS mean values for soil physical properties by traffic level. Values not followed by the same letter within a column are significantly different at α = 0.1.

Traffic	Bulk density (S.E.) (Mg m^{-3})	Ksat (S.E.) (cm h^{-1})	Macroporosity (S.E.) (%)	Microporosity (S.E.) (%)	Penetration depth (S.E.) (cm)
Off	1.39 a (0.01)	21.98 a (2.87)	10.11 a (0.29)	36.23 a (0.28)	32.68 a (0.46)
On	1.42 b (0.01)	20.49 a (2.91)	10.08 a (0.29)	36.08 a (0.28)	29.72 b (0.47)

Table 5
LS mean values for soil chemical properties by traffic level. Values not followed by the same letter within a column are significantly different at α = 0.1.

Traffic	Phosphorus (S.E.) (kg ha^{-1})	Total nitrogen (S.E.) (μg g^{-1})	Carbon (S.E.) (Mg ha^{-1} to 15 cm)
Off	2.46 a (0.10)	889.15 a (22.43)	55.46 a (1.04)
On	2.68 a (0.10)	916.71 a (22.43)	54.31 a (1.06)

Table 6
LS mean values for stand level parameters by traffic level. Values not followed by the same letter within a column are significantly different at α = 0.1.

Traffic	Stand biomass green weight (S.E.) (Mg ha^{-1})	Stand density (S.E.) (no. trees ha^{-1})	Soil + loblolly pine carbon (S.E.) (Mg ha^{-1})
Off	199.2 a (13.46)	750.0 a (43.57)	105.1 a (3.51)
On	179.1 a (13.46)	791.5 a (43.57)	97.7 a (3.51)

Table 7
LS mean values for depth to iron depletion and total porosity analyzed as eight separate treatments. Values not followed by the same letter within a column are significantly different using Fisher's LSD at α = 0.1.

Traffic site preparation	Soil depth to iron depletion (S.E.) (cm)	Total porosity (S.E.) (%)
Off		
Bed	34.82 bc (3.02)	48.02 a (0.76)
D/B	40.32 ab (3.02)	47.80 ab (0.76)
Disk	31.52 cd (3.17)	44.22 d (0.79)
None	31.11 cd (3.02)	44.98 cd (0.76)
On		
Bed	45.09 a (3.02)	45.51 cd (0.76)
D/B	37.25 bc (3.02)	47.55 ab (0.76)
Disk	26.90 d (3.17)	45.16 cd (0.77)
None	25.82 d (3.02)	46.17 bc (0.79)
P-value	< 0.0001	0.0009

3.4. Non-site prepared soils

We compared all measurements on non-site prepared primary skid trails to those taken on soil with no obvious traffic disturbance or site preparation treatment. Soil physical properties (Table 8), chemical properties (Table 9), and stand level metrics (Table 10) did not differ significantly between the Off-None and On-None treatment combinations.

4. Discussion

4.1. Effects of site preparation on soil physical properties

Twenty three years after planting, Bed and D/B have lower bulk density and greater Ksat and macroporosity values relative to Disk and None. The trends in bulk density and Ksat may be linked to enhanced root development in beds (Haines and Pritchett, 1965; Schultz, 1973). Bed and D/B also have significantly greater stand density than Disk and None (Table 3) due to improved soil aeration and seedling survival at stand establishment (Aust et al., 1998b). The treatments with greater stand density are likely subjected to more prolific rooting activity, which decreases bulk density and increases Ksat over time by forming voids and incorporating organic matter (Larson and Allamaras, 1971). Two years after site preparation installation, bulk density and Ksat showed little response to site preparation (Aust et al., 1998b), suggesting these measurements were generally unaffected by tillage, but instead, a mechanism that is active over time. However, favorable macroporosity conditions for Bed and D/B treatments were observed two years after treatment installation (Aust et al., 1998b), suggesting tillage did directly benefit macroporosity. Mean macroporosity values for Disk and None are of interest because they remain slightly below the 10% threshold for adequate root aeration suggested by Vomicil and Flocker (1961) 23 years after stand establishment (Table 1). The macroporosity value for Off-None (Table 2.8) suggests that soils at these sites are inherently aeration deficient, and Bed and D/B may alleviate this limitation. Although differences in bulk density are significant, a 0.07 Mg m^{-3} discrepancy is unlikely to cause substantial decline in pine productivity, and all values are below the growth limiting value for the surface texture of all soil series in the study area (Table 1) (Dadow and Warrington, 1983). The small differences in microporosity and total porosity values are also unlikely to affect pine productivity,

Table 9
LS mean values for soil chemical properties for non-site prepared treatments. LS means compared using a one-way contrast at α = 0.1.

Treatment combination	Soil depth to iron depletion (S.E.) (cm)	Phosphorus (S.E.) (kg ha^{-1})	Nitrogen (S.E.) (μg g^{-1})	Carbon (S.E.) (Mg ha^{-1} to 15 cm)
Off-None	31.11 (3.02)	2.55 (0.18)	1016.02 (50.68)	65.67 (2.50)
On-None	25.82 (3.02)	2.76 (0.18)	1109.65 (50.68)	66.67 (2.55)
P-value	0.2169	0.4350	0.1933	0.8391

Table 10
LS mean values for stand level parameters of non-site prepared treatments. LS means compared using a one-way contrast at α = 0.1.

Treatment combination	Stand biomass green weight (S.E.) (Mg ha^{-1})	Stand density (S.E.) (No. Trees ha^{-1})	Soil + loblolly pine carbon (S.E.) (Mg ha^{-1})
Off-None	105.7 (27.82)	403.7 (119.54)	93.7 (7.24)
On-None	119.8 (27.82)	493.4 (119.54)	96.0 (7.24)
P-value	0.7209	0.5973	0.8259

Table 8
LS mean values for soil physical properties of non-site prepared treatments. LS means compared using a one-way contrast at α = 0.1.

Treatment combination	Bulk density (S.E.) (Mg m^{-3})	Ksat (S.E.) (cm h^{-1})	Macroporosity (S.E.) (%)	Microporosity (S.E.) (%)	Total porosity (S.E.) (%)	Penetration depth (S.E.) (cm)
Off-None	1.43 (0.02)	6.09 (5.64)	8.26 (0.57)	36.73 (0.56)	44.98 (0.76)	29.49 (0.94)
On-None	1.43 (0.02)	19.36 (5.92)	9.28 (0.59)	36.90 (0.56)	46.17 (0.79)	27.26 (0.98)
P-value	0.9279	0.1051	0.2121	0.8338	0.2763	0.1005

despite statistically significant differences in total porosity.

It is striking that absolute bulk density values measured in this study are higher than those reported in Aust et al. (1998b) for respective site preparation treatments. Abundance of organic logging debris and leaf litter present after salvage logging may have contributed to this response. Organic matter lowers soil bulk density, and it is possible that a substantial proportion of organic logging debris oxidized between the 1992 and 2015 measurements, allowing mineral soil particles to settle into a smaller volume. Likewise, beds may have settled over time in the Bed and D/B treatments. Systematic differences in subsample collection may have also been involved.

Results of this study contradict findings of Eisenbies et al. (2007) at stand age 7 years and Lang et al. (2016) at age 17 years on another wet mineral flat. Eisenbies et al. (2007) and Lang et al. (2016) concluded that bedding does not provide long term advantages for bulk density, Ksat, or macroporosity relative to non-site prepared soils. The recovery of compacted soils among treatments in Eisenbies et al. (2007) and Lang et al. (2016) was largely attributed to 2:1 shrink-swell clays, which act to homogenize soil physical properties of different treatments over time. Soils at our long term study sites have siliceous minerology and low shrink-swell potential (Long, 1980). Additionally, experimental controls on seedling survival through the first growing season and unusual weather patterns from years three through five at the Eisenbies et al. (2007) and Lang et al. (2016) sites resulted in more uniform stand density for bedded and non-site prepared treatments. Therefore, the similar levels of rooting activity would not be expected to create appreciable differences in soil physical properties among treatments, as suggested for our study. Gent et al. (1984) reported that disking restored bulk density and macroporosity, but failed to restore Ksat, to productive levels after harvesting on an upland piedmont soil in North Carolina. At the study sites, disking did not provide benefits in terms of macroporosity or bulk density after two years (Aust et al., 1998b) or 23 years (Table 1). Inherent differences in soil properties and moisture content between piedmont uplands and coastal plain wet flats may contribute to the varied results observed in the effectiveness of disking; however, not enough information is provided to determine specific treatment-soil relationships. Gent et al. (1984) and Aust et al. (1998b) are consistent in suggesting that disking is ineffective at restoring Ksat on disturbed sites because it does not enhance soil structure. This remains evident at the study sites after 23 years (Table 1).

The penetration depth measurements provide an objective comparison of soil mechanical resistance to root penetration. The significantly greater penetration depths achieved for Bed and D/B relative to Disk and None are probably related to soil bulk density and the depth of topsoil (Table 1). Soil penetration resistance is positively correlated with bulk density (Greacen and Sands, 1980; Sands et al., 1979), and Bed and D/B have slightly lower bulk densities than Disk and None. Bedding redistributes topsoil from furrows to a continuous linear mound, providing a greater depth of easily penetrated topsoil than Disk and None. Carter et al. (2007) also reported lower penetration resistance in bedded treatments relative to non-bedded treatments at a similar site. Penetration resistance typically increases with soil depth in wet pine flats because the argillic horizon is inherently denser than surface horizons (Carter et al., 2007). Observation during data collection confirmed that penetration increments with each driving anvil blow decreased once the penetrometer was in contact with the argillic horizon.

4.2. Effects of site preparation on soil chemical properties

Soil depth to iron depletion provides an index of aerated soil depth. Iron depletions in wetland soils occur due to reduction of ferric iron to ferrous iron and subsequent translocation of ferrous iron. Hence, iron depletions are an indicator that anoxic conditions induced by prolonged saturation have occurred at that location in a soil profile (Bartlett and James, 1993). Perhaps the main reason greater soil depth to iron depletion for Bed and D/B relative to Disk and None was observed is that bedding forms a soil surface several centimeters above the original soil surface (Table 2). This is consistent with numerous studies that have reported increases in aerated soil depth as a result of bedding (Aust et al., 1998b; McKee and Shoulders, 1974; McKee and Wilhite, 1986; Sanchez et al., 2006; Xu et al., 2002). Additionally, the enhanced Ksat and macroporosity for Bed and D/B treatments would promote more rapid soil drainage and oxygen diffusion which favors oxidation (Table 1). Although Ksat and macroporosity were directly measured only at the soil surface, it is possible that the trends observed persist to some depth because of the greater stand density and enhanced rooting activity in the Bed and D/B treatments (Haines and Pritchett, 1965; Schultz, 1973).

It has been suggested that planting beds may concentrate soil nutrients and organic matter (Attiwill et al., 1985; Pritchett, 1979); however, Scheerer (1994) did not detect a significant difference in Total Kjeldahl Nitrogen, soil phosphorus, or organic matter between site preparation treatments (although None was omitted from analysis) at stand age two years at the study sites. At stand age 23 years, the significantly different total nitrogen and phosphorus contents suggest that site preparation has affected these measurements over time (Table 2). The lower nitrogen and phosphorus concentrations in Bed and D/B treatments generally correspond to the greater above ground stand biomass in these treatments (Table 3); however, the small differences in soil phosphorus content are probably not biologically significant. Soils in wet pine flats often have inherently poor nutrition (Allen and Campbell, 1988), and phosphorus content for all treatments are below 3 $\mu g\, g^{-1}$ (data not shown), which is considered deficient for loblolly pine (Wells et al., 1973). Adequate aeration was the principal limiting factor to seedling survival, and Bed and D/B treatments alleviated this limitation, as suggested by Aust et al. (1998b) and the current trends in stand biomass and stand density. Thus, by providing initial advantages for seedling survival, the Bed and D/B treatments may have resulted in more of the total nitrogen in the system to be allocated in tree biomass. Preferential soil nutrient depletion in beds was suggested as the cause for reduced second rotation slash pine productivity on beds established prior to the first rotation by Tiarks and Haywood (1996) on a Gulf coastal plain wet flat. This theory is consistent with trends in above ground biomass and soil nitrogen concentration at our study sites. Furthermore, nitrogen dynamics as directly influenced by bedding on wet flats provides evidence that a greater proportion of nitrogen in the system is partitioned as tree biomass. Eisenbies et al. (2007) reported significantly greater nitrogen mineralization rates as a result of bedding on a similar site in South Carolina. On a wet flat in Florida, Burger and Pritchett (1988) documented greater foliar nitrogen concentrations, greater concentrations of plant available nitrogen, and lesser concentrations of total nitrogen in bedded treatments relative to non-bedded treatments. It is possible that nitrogen dynamics at the study sites are similar to those observed by Burger and Pritchett (1988), although this cannot be confirmed since only total soil nitrogen was measured.

The lower soil carbon quantities in the Bed and D/B treatments are likely the result of greater soil aeration provided by these treatments (Table 2). The rate at which carbon in organic matter is converted to carbon dioxide via microbial decomposition processes is positively correlated with soil aeration (McLatchey and Reddy, 1998). Soil is clearly more aerated in the Bed and D/B treatments based on the values for Ksat, macroporosity (Table 1) and depth to iron depletion (Table 2). Scheerer (1994) did not detect significantly different organic matter content by site preparation treatment at stand age two years, suggesting the present values are not the result of mixing E and B horizon material with the original A horizon via bedding. Lower soil carbon concentrations as a result of soil physical conditions created by bedding have also been reported on wet flats in Louisiana (McKee and Shoulders, 1974) and Florida (Burger and Pritchett, 1988). Additionally, field observations indicated that Disk and None treatments contained greater biomass of herbaceous vegetation than Bed and D/B, but this observation was not quantified. Rapid root turnover associated with herbaceous vegetation may have been another contributing factor to greater soil carbon accumulation in Disk and None treatments. These findings exemplify that site preparation can influence the form in which carbon is stored in wet pine flats. Bed and D/B treatments store more carbon in above-ground loblolly pine biomass than Disk and None (Table 3), but Disk and None provide more long term carbon storage in soil (Table 2). These mechanisms of carbon storage offset, such that total carbon stored in soil and loblolly pine biomass per unit of area (soil + loblolly pine carbon) is not significantly different by site preparation treatment (Table 3). It is important to acknowledge that carbon storage was not quantified for roots and vegetation other than loblolly pine. A more thorough investigation is required to obtain greater insight on carbon cycling and storage at the study sites.

4.3. Recovery of primary skid trails

Rubber-tired skidder traffic at the study sites initially resulted in greater bulk density, lower macroporosity, lower Ksat, shallower depth to water table, and soil displacement (Aust et al., 1995; Aust et al., 1998b). Numerous other studies have documented similar short term changes in soil properties as a result of heavy equipment traffic (Aust et al., 1993; Aust and Lea, 1992; Dickerson, 1976; Gent et al., 1983; Hatchell et al., 1970; Horn et al., 2004). Twenty-five years after salvage logging, minimal differences in soil properties and stand productivity remain evident when considering the main effect of traffic (Tables 4, 5, 6, and 7). Although the difference in bulk density is significant by traffic level, a 0.03 Mg m^{-3} difference is unlikely to influence most soil processes, and the higher of the two average bulk densities is below the growth limiting value suggested by Dadow and Warrington (1983) for the surface texture of all soil series at the study sites. It is possible that the significantly lower penetration depth for On is somewhat linked to the greater bulk density for On; however, most of this difference is probably due to soil displacement. Cross-sectional profiles of On treatment plots surveyed by Tippett (1992) showed that elevations of the soil surface were clearly altered by skidder traffic. Cross-sectional profiles were not measured for this study, but it remains visually evident that soil surfaces in many On treatment plots are lower than adjacent, undisturbed soil surfaces. Consequently, on average, the penetrometer had less soil depth to penetrate before coming in contact with the argillic horizon. Even so, the difference in average penetration depth of approximately 3 cm may not have substantial influence on forest productivity. All other soil and stand measurements are generally similar among traffic levels.

A contrast was used to compare Off-None and On-None to determine if soils in primary skid have trails recovered to the state of an undisturbed soil, without incorporating any influences of site preparation. Two years after disturbance, Off-None had significantly lower bulk density and significantly greater macroporosity and Ksat than On-None (Aust et al., 1998b). At stand age 23 years, there are no significant differences in soil properties or stand productivity (Tables 8, 9, and 10). The current similarities in soil properties and stand productivity between traffic levels, with and without site preparation, suggest that natural recovery mechanisms have acted over time to restore primary skid trails. The most effective natural recovery mechanisms at the site are probably wet-dry cycling, rooting activity, and bioturbation by soil organisms. Other long term studies have suggested soil shrink-swell (Lang et al., 2016; McKee et al., 2012) and sediment deposition (McKee et al., 2012) as natural soil recovery after severe skidder traffic disturbance, but these mechanisms are not active at the study sites. Dominant soils have siliceous minerology with low shrink-swell potential (Long, 1980) and are isolated from fluvial processes. Wet-dry cycling favors soil aggregation, which improves macroporosity and Ksat (Larson and Allamaras, 1971). Frequent ponding and dry-down of water was observed during field data collection. Root and soil organism activity form channels and incorporate organic matter in soil, enhancing physical properties. It should be noted that traffic did not significantly affect seedling survival through age four years (Aust et al., 1998b). Had survival been reduced by equipment traffic as reported by Hatchell et al. (1970) and Lockaby and Vidrine (1984) on comparable sites, rooting activity of trees may have a less important recovery mechanism, and conclusions regarding stand productivity may be different. Recovery of soil properties has been also reported by Lang et al. (2016) and resilience of stand productivity by Passauer et al. (2013) and Sanchez et al. (2006) following harvest related disturbance in wet pine flats. Coupled with evidence provided by these studies, our research suggests that site preparation is not required to ameliorate the effects of harvesting disturbance on soil properties and stand productivity in some wet pine flats. Natural recovery mechanisms may be sufficient to restore soil properties and productivity levels on heavily disturbed, compacted, or rutted southeastern coastal plain sites.

5. Conclusion

At stand age 23 years, bedding and disking with bedding site preparation treatments were effective in enhancing soil properties that influence loblolly pine growth on wet pine flats. Bedding and disking with bedding improved soil aeration by increasing macroporosity and creating an elevated soil surface. Increasing aeration via these mechanisms may favor greater long term root development and nutrient availability. Bulk density and saturated hydraulic conductivity decreased and increased, respectively, over time in the bedding and disking with bedding treatments, perhaps as a result of root development. Disking did not provide appreciable long term advantages in terms of soil properties or stand productivity relative to non-site prepared soils. Disking with bedding did not yield substantial long term advantages over bedding alone, but is more expensive to implement. Thus, bedding is recommended to create soil conditions that improve pine establishment and productivity on wet pine flats that are aeration deficient. Detailed hydrologic and soil laboratory data are often not readily available when making forest management prescriptions; however, hydrophytic plant communities and soil redoximorphic features are stable, relatively easily assessed characteristics that may indicate appropriate management practices to successfully regenerate loblolly pine on a site.

Initially, primary skid trails exhibited substantially altered soil properties, but the study sites apparently have sufficient natural recovery mechanisms such that soil properties and stand productivity were restored by stand age 23 years. Results of this study imply that site preparation is not necessary, if prescribed only to ameliorate disturbance caused by ground-based timber harvesting in wet pine flats. Recovery mechanisms may include rooting activity, wet-dry cycling, and bioturbation by soil organisms. Despite the efficacy of natural recovery mechanisms at the study sites, it is recommended that the spatial extent of equipment traffic be minimized to avoid unnecessary short term changes in soil processes, and challenges that may arise due to slowly acting recovery mechanisms.

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