Long Term Effects of Wet Site Timber Harvesting and Site Preparation on Soil Properties and Loblolly Pine (*Pinus taeda* L.) Productivity in the Lower Atlantic Coastal Plain

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ABSTRACT (ACADEMIC)

Short term studies have suggested that ground based timber harvesting on wet sites can alter soil properties and inhibit early survival and growth of seedlings. Persistence of such negative effects may translate to losses in forest productivity over a rotation. During the fall and winter of 1989, numerous salvage logging operations were conducted during high soil moisture conditions on wet pine flats in the lower coastal plain of South Carolina following Hurricane Hugo. A long-term experiment (split-plot within an unbalanced randomized complete block design) allowed assessment of long term effects of rutted and compacted primary skid trails and subsequent site preparation on soil properties and loblolly pine (*Pinus taeda* L.) productivity. The experiment had 12 blocks, four levels of site preparation as the whole plot factor (bedding, disking with bedding, disking, and no site preparation), and two levels of traffic as the subplot factor (primary skid trail, no obvious traffic). After 23 years, bedding and disking with bedding treatments effectively enhanced soil physical properties and stand productivity via promoting greater survival and stocking, but had little effect on the size of individual trees relative to disking and no site preparation treatments. Primary skid trails significantly reduced the size of individual trees, but had no appreciable long term effects on soil properties or stand productivity after 23 years. The study suggests that bedding is the most efficient practice to enhance soil properties, seedling survival, and stand productivity on wet sites. However, site preparation is not necessary for these soils and sites, if strictly intended to restore soil properties and stand productivity in primary skid trails. Reduction in individual tree sizes on primary skid trails emphasizes benefits in minimizing the spatial extent of disturbance.

Long Term Effects of Wet Site Timber Harvesting and Site Preparation on Soil Properties and Loblolly Pine (*Pinus taeda* L.) Productivity in the Lower Atlantic Coastal Plain

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ABSTRACT (GENERAL AUDIENCE)

Heavy equipment traffic associated with ground-based timber harvesting has potential to alter soil properties resulting in lower productivity of the subsequent forest. Various soil tillage techniques have been suggested to offset changes in soil properties and forest productivity on disturbed soils, and to enhance soil properties and forest productivity on undisturbed soils. An experiment was conducted on low-lying Atlantic Coastal Plain sites to compare the effects of four soil tillage treatments (bedding, disking, disking with bedding, no tillage) on soil properties and forest productivity 23 years after treatments were installed. Bedding displaces soil from furrows into continuous, linear mounds called beds, such that bed surfaces are above the original soil surface. Disking is a tillage practice commonly implemented in agriculture. For the disking with bedding treatment, plots were disked followed by bedding. The no tillage treatment served as a control. Additionally, the experiment provided comparison of soil properties and forest productivity between soils heavily disturbed by logging activities and relatively undisturbed soils. Bedding and disking with bedding created favorable, localized soil conditions that promoted greater loblolly pine survival which translated to approximately double the total stand volume per unit area relative to disking and no tillage treatments. Differences in the sizes of individual trees among tillage treatments were minimal. Heavily disturbed soils and soils undisturbed by logging activity were similar in terms of soil properties and loblolly pine volume per unit area; however, individual trees were smaller on heavily disturbed soils. The implications of this study provide practical guidance for forest management decisions. Of treatments compared, bedding is the most efficient to increase total stand productivity on poorly drained sites. Disking with bedding offers no additional benefits, but is more expensive to implement. Results also imply that soils disturbed by logging have potential to recover over time such that long term forest productivity is sustained. However, the reduction in individual tree sizes emphasizes benefits of minimizing soil disturbance during timber harvests.

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1.0 INTRODUCTION

Sustaining forest productivity and forest ecosystem service integrity are guiding principles for sustainable forest management. Globally, the demand for forest ecosystem services is expected to increase simultaneously with decreases in forested land area as a result of human population growth (Burger, 2009; FAO, 2015; Fox, 2000). A key ecosystem service provided by forests is timber production, which ensures stable wood and fiber supplies, thereby providing substantial contributions to the economy. Ground-based forest harvesting systems are common due to operational and economic efficiency (Cambi et al., 2015; Miwa et al., 2004). Heavy equipment traffic integral to these operations can potentially degrade soil properties and affect productivity and function of forest land. For forestry to be sustainable, long term negative impacts on soil properties must be mitigated (Burger, 2009; Fox, 2000).

Forested wetlands present a unique management challenge because they are valued for ecosystem services including biogeochemical transformation, hydrology benefits, wildlife habitat, and carbon storage (Richardson, 1994). These potentially highly productive sites are exceptionally prone to adverse effects of harvesting equipment traffic due to frequent high soil moisture conditions (Miwa et al., 2004; Richardson, 1994). The contiguous United States contains an estimated 44.6 million ha of wetlands, which is approximately one-half of the estimated extent of 89 million ha of wetlands existing prior to European settlement (Dahl, 2011). The loss in ecosystem services associated with this decline in wetland area has been acknowledged, and federal laws have been enacted in an effort to conserve wetlands, including section 404 of the Federal Water Pollution Control Act of 1972 (the Clean Water Act). Wetlands are under jurisdiction of the Clean Water Act if they satisfy defined criteria for hydric soils, hydrophytic vegetation, wetland hydrology, and a nexus to waters of the United States. As a result of wetland creation and restoration efforts, some years show a net gain in wetland area (Dahl, 2011). However, it has been suggested that created and restored wetlands do not provide the same ecological and functional value as minimally disturbed wetlands (e.g. Hoeltje and Cole, 2007; Hossler et al., 2011; Jessop et al., 2015; Moreno-Manteos et al., 2015, 2012; Richardson, 1994; Sutton-Grier et al., 2010). Silviculture has been reported as a major cause of decline in forested wetland area between 2004 and 2009 (Dahl, 2011), though this is more likely short term classification as a different type of wetland following harvest rather than conversion to upland. Regardless, it would be advantageous to enhance timber production without compromising the jurisdictional status or functional capacity of wetlands.

In the Southeastern U.S. coastal plain, pine plantations are often intensively managed to efficiently provide timber and ecosystem services (Fox, 2000; Stanturf, et al., 2003). These sites commonly occur on “wet pine flats” which are characterized by limited lateral relief, a drainage restricting argillic horizon, and may qualify as jurisdictional wetlands (Allen and Campbell, 1988; Harms et al., 1998). Frequent high soil moisture conditions and management practices involving heavy equipment make these sites vulnerable to soil disturbance and potential productivity decline (Miwa et al., 2004). Some wetland sites have natural recovery mechanisms that make them resilient to long term negative effects of wet weather harvesting, but complete recovery is not certain on all sites (Eisenbies et al., 2007; Lang et al., 2016; McKee et al., 2012). Mechanical site preparation has been suggested as a means to ameliorate disturbed soil properties or enhance undisturbed soils and to ensure forestry on coastal plain sites is sustainable (Allen and Campbell, 1988; Fox, 2000; Morris and Lowery, 1988 Reisinger et al., 1988).

1.1 Literature Review

1.1.1 Harvesting Disturbance

Modern forest harvesting operations rely upon heavy equipment due to operational and economic efficiencies. Although best management practices recommend avoiding harvesting under wet conditions, the high proportion of timberland located on wet sites, frequent precipitation, slow infiltration and restricted drainage, and demand for fiber concomitantly ensure that wet weather harvest will occur (Aust and Blinn, 2004; Miwa et al., 2004). Forest harvesting equipment may traffic between 10 and 70 percent of a harvest area during clearcutting, resulting in potential for extensive soil compaction and rutting (Cambi et al., 2015). The greatest increases in bulk density and soil strength occur during the first few machine passes. Further compaction becomes more gradual with each additional pass (Gayoso and Iroume, 1991; Hatchell et al., 1970; Williamson and Neilsen, 2000). This indicates that it could be advantageous to minimize the spatial extent of trafficking, restricting damage to a smaller area.

Heavy equipment traffic creates both normal and shearing forces. Normal forces exert downward pressure on soil as a result of gravitational acceleration. Shearing forces are multidirectional forces, such as vibration and wheel slip, which interrupt contact points between soil particles, reorienting particles relative to one another and altering soil structure (Miwa et al., 2004; Cambi et al. 2015). The degree of disturbance caused by these forces varies with weight of the machine, number of machine passes, ground pressure exerted, ground cover, soil texture, soil organic matter content, soil surface slope, and soil moisture content at the time of disturbance (Cambi et al., 2015; Greacen and Sands, 1980; Naghdi et al., 2016). In general, soil disturbances associated with the normal and shearing forces induced by forest operations are categorized as compaction or rutting/puddling (Aust et al., 1998a).

1.1.2 Compaction and Rutting

Soil compaction and rutting are distinct disturbances that can occur as a result of harvesting traffic may affect soil physical properties differently (Aust et al., 1995). Compaction is the physical compression of soil under a load (Greacen and Sands, 1980). Maximum compaction potential occurs when a soil is at field capacity and has reached its plastic limit. At this moisture content, water films lubricate soil particle to particle contact points, reducing the ability to support a load (Akram and Kemper, 1979). The soil volume reduction occurs at the expense of air filled pore space (Greacen and Sands, 1980). At lower water potentials, higher frictional forces between soil particles resist compaction.

Rutting (puddling) is the destruction of soil structure that occurs when external forces are applied to soil when moisture content nears saturation and the soil has approached or surpassed its liquid limit. Soil is less compressible when all pores are filled with water (Aust and Lea, 1992), resulting in displacement and churning instead of compaction (Miwa et al., 2004). Saturated soil flows outward as a liquid in response to load application (Aust et al., 1995). During harvesting operations, displaced soil forms ruts in the shape of equipment tires or tracks with berms along either side of the rut (Aust et al., 1993).

1.1.3 Effects of Compaction on Soil Properties

Soil bulk density is increased by compaction; the mass of soil solids is forced into a smaller volume. The reduction in volume occurs due to the collapse of pore spaces, with larger macropores being collapsed before micropores (Greacen and Sands, 1980). Macropores are large enough for water to drain under the force of gravity; therefore, macropore reduction may cause a reduction in hydraulic conductivity as well.

Aust et al. (1995) observed a bulk density increase of 20%, macropore space decrease of 27%, and a hydraulic conductivity decrease of 88% on compacted skid trails in wet pine flats in the South Carolina lower coastal plain. At a comparable site on the South Carolina coastal plain, Aust et al. (1998b) reported similar trends in soil physical property degradation due to compaction resulting from ground-based skidding. Gent et al. (1983) reported significant increases in bulk density to a depth of 30 cm, and decreases in hydraulic conductivity and macroporosity to a depth of 15 cm in North Carolina coastal plain skid trails.

Moehring and Rawls (1970) examined wet weather trafficking with a crawler tractor on silt loams having a drainage restricting fragipan in Arkansas and reported bulk density increases of 13% and macroporosity decreases of 49%. Traffic conditions were replicated during the dry season and no significant changes in soil properties were detected. These findings suggest an advantage of operating under dry conditions, but are met with logistic challenges that would arise due to long periods of down time that would occur on poorly drained sites and wetlands.

Additionally, soil aeration is reduced following compaction and destruction of macropores. Startsev and McNabb (2009) investigated the effects of harvesting-induced compaction on soil morphology, aeration regime, and redox potential across a drainage class gradient in a Canadian boreal forest. Moderately well drained soils were found to be most prone to becoming aeration limiting (based on a 10% aeration porosity threshold) and undergo a change in drainage class. Well drained soils maintained sufficient aeration such that morphological indicators of drainage class remained the same following compaction. Imperfectly drained (somewhat poorly drained) and poorly drained soils had restricting aeration values irrespective of compaction level and morphological indicators did not suggest a change in drainage class. In wetland sites, aeration deficits caused by macropore destruction can be compounded by water table rise following harvest that occurs due to the reduction in evapotranspiration (Sun et al., 2000; Xu et al., 2002). Aust et al. (1995) isolated the effects of soil compaction on the water table elevation and observed increases of eight cm, 17 cm, and 43. cm on poorly drained, somewhat poorly drained, and moderately well drained sites, respectively.

Soil mechanical resistance, sometimes referred to as soil strength, is measured and expressed as soil cone index or mechanical resistance. Soil mechanical resistance provides an index of a soil's bearing capacity and resistance to root elongation and reflects soil moisture transience (Busscher et al., 1997). Soils exhibiting higher bulk densities tend to have higher soil strength when held at the same matric potential (Bradford, 1986). Hatchell et al. (1970) reported surface soil penetration resistance values of 107.9, 205.9, 274.6, and 333.4 kPa for undisturbed areas, secondary skid trails, primary skid trails, and decks, respectively at various logging sites in the lower coastal plain of South Carolina and Virginia. A similar trend in soil strength across a traffic gradient was observed by Lockaby and Vidrine (1984) in the Louisiana coastal plain. The values reported are 28.6, 37.4, 42.0, 65.4, 70.7 kPa for undisturbed areas, road borders, secondary roads, primary roads, and decks, respectively. These studies suggest that soil strength increases with traffic intensity.

Compaction in wetlands may not always result in increased soil strength because volumetric water content is increased (Burger et al., 1989). Aust et al., (1998b) reported no significant increase in soil strength due to compaction in a wet pine flat following harvest. Indeed, under saturated conditions the soil strength may not increase following traffic disturbances, but severely trafficked soils may have root restricting soil mechanical resistance values after the site dries. This is evidenced by mechanical resistance values that increase with severity of visually determined compaction intensity classes on upland soils in New Zealand (Murphy and Firth, 2004) and Malaysia (Jusoff and Majid, 1992).

Skidder trafficking both directly and indirectly influences chemical properties. Naghdi et al. (2016) document significantly lower concentrations of organic carbon, phosphorus, nitrogen, and potassium on skidder trafficked upland soils in Iran relative to adjacent, undisturbed soils. Increasing frequency of machine passes further reduced these nutrient concentrations. It is suggested that skidding directly influenced these chemical properties by displacing the litter and topsoil layers and mixing the topsoil with less fertile subsoil. Soil compaction may indirectly reduce available nutrient concentrations by altering the aeration regime (Greacen and Sands, 1980).

1.1.4 Effects of Rutting (Puddling) on Soil Properties

Soil churning or puddling effects on macroporosity and hydraulic conductivity may be similar to compaction, but alterations in bulk density are more variable. The changes in bulk density as a result of puddling are due to the elimination of macropore space via mechanical churning under high moisture conditions and subsequent settling of soil particles into reorganized masses. Puddling a well aggregated, porous soil tends to increase bulk density, while puddling compacted soils may disperse particles and lower bulk density (Sharma and DeDatta, 1986). Furthermore, churning may incorporate organic matter (litter layer and logging debris) into the soil profile and offset bulk density alterations (McKee et al., 2013).

Mousavi et al. (2009) experimented with a silty clay loam at various puddling intensities in laboratory and field tests and observed that bulk densities were reduced by approximately 25% regardless of puddling intensity. Percolation rates were reduced significantly as puddling intensity increased. Naphade and Ghildyal (1971) conducted a similar experiment with an aggregated sandy clay loam and reported opposite effects on bulk density. Decreases in specific volume from 0.714 to 0.591 cm^3/g in the laboratory and from 0.714 to 0.615 cm^3/g in the field were observed. Hydraulic conductivity was reduced from 0.192 cm/hr to 0.019 and 0.054 cm/hr in the laboratory and field, respectively.

When forested wetlands are harvested under soil moisture contents exceeding field capacity, equipment traffic forms ruts with characteristics of puddled soil. Aust et al. (1995) stated that soil displaced from skidder ruts had no significant increases in bulk density relative to undisturbed areas, but values from within ruts were potentially root limiting. Average macroporosity and hydraulic conductivity in rutted skid trails were decreased to 60% and 8%, respectively, of values obtained from nontrafficked plots. In a comparable study, Aust et al. (1998b) reported an increase in mean bulk density from 1.26 to 1.46 Mg/m^3, mean macroporosity decrease from 13.0 to 6.9% and mean hydraulic conductivity decrease from 8.9 to 0.6 cm/hr as a result of rutting.

Rutting may have adverse impacts on site hydrology that exceed those resulting from compaction. In rutted soils, hydraulic conductivity may not only be reduced by destruction of macropores, but also the parallel setting of suspended clay particles, which creates a sealing effect (Sharma and DeDatta, 1986). Aust et al. (1998b) reported significantly higher water tables in rutted plots relative to undisturbed and compacted plots. Similarly, Aust et al. (1993) found decreases in macroporosity, hydraulic conductivity, and water table depth relative to pre-disturbance values on rutted skid trails in a wet pine flat in South Carolina. The suggested cause of elevated water tables is the puddled walls of ruts which restricted the horizontal movement of water.

Carter et al. (2007) compared the effect of various soil disturbance classes on soil strength in a wet pine flat on the South Carolina coastal plain. Rutting and puddling were classified as separate disturbances with disturbance intensity increasing from shallow rutting to deep rutting to puddling. Average soil strength decreased as intensity of disturbance increased. This likely reflects the trend of preharvest soil moisture conditions, because higher soil moisture contents favor more intense disturbance.

1.1.5 Effects of Altered Soil Properties on Tree Establishment and Growth

Tree root growth is influenced by a variety of soil related factors, including soil strength, aeration, water, and nutrient availability (Greacen and Sands, 1980). Minimally disturbed forested wetland soils typically have low bulk densities (<1.2 Mg/m^3) and high macropore percentages in surface horizons favorable to tree root growth. In coastal plain wet pine flats, aeration is commonly a limiting factor to root growth (Allen and Campbell, 1988). Vomocil and Flocker (1961) identified 10% as the macroporosity threshold at which roots have sufficient oxygen availability. Thus, destruction of aeration porosity by traffic under wet conditions has potential to further inhibit site productivity.

Roots larger than soil pores must physically displace soil to grow. If the forces exerted by roots cannot overcome the soil strength, growth will be limited (Greacen and Sands, 1980). In a greenhouse study, Mitchell et al. (1982) observed root and height growth in loblolly pine seedlings inversely proportional to bulk density. Additionally, nutrient deficiency was reported in seedlings planted in soil with a bulk density of 1.8 g/cm^3. More coarsely textured soils have larger pore radii than fine textured soils and provide less resistance to root growth. Daddow and Warrington (1983) estimate a growth limiting bulk density of 1.75 Mg/m^3 for sandy soils and 1.4

Mg/m^3 for clays. Sands et al. (1979) report 3 MPa as a threshold penetration resistance value, above which radiata pine (*Pinus radiata*) roots are severely restricted.

Data from Lockaby and Vidrine (1984) demonstrates the effect of traffic intensity on tree survival and growth. Mean loblolly pine heights at age five years were 0.79, 1.2, 1.7, 1.7, and 1.95 meters for decks, primary roads, secondary roads, road borders, and nontrafficked areas, respectively. Survival rates were 1347, 1905, 8406, 10092, and 15696 trees/hectare in the same respective order. In a South Carolina wet pine flat, Scheerer (1994) documented mean height and DBH of two year old loblolly pine seedlings as 0.6 m and 0.9 cm in nontrafficked plots. Mean values in compacted and rutted plots were 0.2 m and 0.4 cm, for height and DBH, respectively. Compacted and rutted plots exhibited significantly higher bulk density and significantly lower macroporosity and hydraulic conductivity. Naghdi et al., (2016) exemplify a response of upland hardwoods to different traffic intensities. Seed germination rate, root growth, and height of velvet maple (*Acer velutinum*) decreased significantly with increasing traffic frequency.

In the lower coastal plain of South Carolina and Virginia, Hatchell et al. (1970) found lower stocking and growth of naturally regenerated loblolly pine seedlings after one growing season in primary skid trails than undisturbed areas. Impaired aeration was suggested as the primary limiting growth factor, while increases bulk density and soil strength were also suspected of reducing growth. Moehring and Rawls (1970) reported significant reductions in basal area growth for five years in response to increased bulk density and decreased macroporosity following wet site trafficking.

Excessive moisture stress is a common challenge to regeneration on wet flats (Allen and Campbell 1988). Following harvests, water tables rise in response to reduced transpiration as well as altered hydrologic properties of soil. Water table rise following harvests in wet flats attributed to reduced transpiration have been reported as 21 cm (Xu et al., 2002) and 32 cm (Sun et al., 2000). Aust et al. (1993, 1995) isolated the effect of soil disturbance on water table depth and reported rises of 17 to 43 cm. Elevated water tables, especially in combination with reduced aeration porosity, may prevent adequate oxygen diffusion in the rooting zone. The rise in water tables following harvest is another rationale for use of mechanical site preparation techniques such as bedding or mounding, which allow planted seedlings to survive until transpiration rates have recovered (Harms et al., 1998).

While numerous studies associate soil compaction with only negative effects on forest productivity (Aust et al., 1998b; Lockaby and Vidrine, 1984; Mitchell et al., 1982; Moehring and Rawls, 1970; Naghdi et al., 2016; Reisinger et al., 1988; Scheerer et al., 1994; Wert and Thomas, 1981;), Gomez et al. (2002) demonstrate that this relationship is a more complex interaction of soil texture, physical properties, and moisture regime which may have positive outcomes. Similar levels of compaction, relative to initial bulk density, were attained on a clayey, loamy, and sandy loam soils in the Sierra Nevada Mountains. Compaction reduced stem volume of ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) significantly on clayey soils by 45%, insignificantly on loamy soils by 6%, and significantly increased stem volume on sandy loams by 173%. Available water content was not significantly altered by compaction in clayey soils, but was significantly increased in loamy and sandy loam soils. Increases in mechanical resistance and low porosity are suggested causes for compaction induced growth reduction on clayey soils. Although the loamy soils had higher mechanical resistance values than clays, tree growth was not significantly reduced because adequate porosity and favorable moisture regimes were maintained. Compacting the sandy loam apparently resulted in a pore size distribution that improved water retention in a soil that was previously excessively drained. Similarly, Ares et al. (2005) report early growth gains of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) on compacted plots in the coastal range of Washington. Compacting the andisols of extremely low bulk density (0.59 Mg/m^{-3} at 0-16 cm depth) and high macroporosity (43% at 0-16 cm depth) significantly increased plant available moisture capacity, which is suggested as the reason for growth increases. These studies demonstrate that the effects of soil disturbance on tree growth are soil, site, and species specific. However, lower bulk density typically promotes greater root growth, and allows trees to adapt to a wider range of soil moisture contents (Siegel-Issem et al., 2005).

1.1.6 Natural Recovery and Resilience of Soil Physical Properties and Productivity

The extent and time frame for natural reconciliation of damaged soil properties and forest productivity is site specific (Miwa et al., 2004). Mechanisms attributed to natural recovery include freeze-thaw cycles, wet-dry cycles, shrinking and swelling of clays, bioturbation by soil fauna, rooting activity, and sediment inputs (Greacen and Sands, 1980; Hatchell and Ralston, 1971; Larson and Allamaras, 1971; McKee et al., 2012). Freeze-thaw, wet-dry, and shrink-swell cycles can accelerate the formation of aggregates (Larson and Allamaras, 1971). Wet-dry cycles may have a profound impact in wetlands due to cyclic hydrologic fluxes. Soil macro fauna and plant roots form macropores and incorporate organic matter to soil. Although burrowing and root expansion must compress soil in the immediate vicinity, macropores remain and the result is usually a decrease in average bulk density (Larson and Allamaras, 1971).

Dickerson (1976) predicted a 12 year period for bulk density and macroporosity to recover to pre-harvest levels in wet weather skidder tracks in the Northern Mississippi coastal plain. Similarly, Hatchell and Ralston (1971) estimated bulk density recovery time of 18 years in the Atlantic coastal plain. Rab (2004) reported macroporosity increases of 100% ten years after harvesting on primary skid trail, secondary skid trails, and log landings in an upland setting. However, significant bulk density decreases after 10 years were only found in secondary skid trails. Primary skid trail bulk densities remained 51% higher than undisturbed areas.

Some forested wetlands apparently have sufficient recovery mechanisms that make them robust to the effects of wet weather harvesting. McKee et al. (2012) reported no apparent negative effects on stand growth and composition 24 years after rutting in a tidal cypress-tupelo wetland. This occurred despite significantly reduced hydraulic conductivity and aeration immediately after harvest (Aust and Lea, 1992). The resilience of this site is attributed to the improvement of soil physical properties through the shrinking and swelling of clays, improvement of aeration and nutrient additions from sediment deposition, and accidental hydrologic and microtopographic impacts of traffic that favored the growth of desirable species (McKee et al., 2012).

Eisenbies et al. (2004, 2005) and Passauer et al. (2013) concluded that wet weather harvesting was no more detrimental to stand biomass accumulation than dry weather harvesting after 5 and 16 years, respectively, in a South Carolina wet pine flat. Unintentional introduction of microtopography and competition suppression are suggested causes for the successful growth on wet harvested sites. One caveat to this study was the unusually dry season that followed planting, which may have eliminated the excess moisture stress factor that is commonly threatens seedling survival on wet pine flats (Allen and Campbell, 1988; Eisenbies et al., 2004, 2005; Passauer et al., 2013). Lang et al. (2016) assessed soil physical properties at this site 17 years after harvest and detected no significant differences between wet and dry weather harvest treatments and determined that soil physical properties had generally recovered. Similarly, Tiarks (1990) concluded that wet weather harvesting did not reduce height nor diameter growth of slash pine relative to dry weather harvesting (when sheared) on Caddo series soil. While soil properties were not directly measured for this study, it is suggested that undisturbed Caddo soils have an inherently low macroporosity percentage so trafficking does not result in reduced drainage or aeration.

1.1.7 Mechanical Site Preparation to Accelerate Recovery

Some wetland sites resist long term losses in productivity as a result of altered soil physical properties (Lang et al., 2016; McKee et al., 2012; Passauer et al., 2013). However, well documented detrimental effects, slow recovery, and overall unpredictability of site specific growth response to harvest disturbance justify the implementation of site preparation to mitigate potential impacts of wet site harvesting (Aust et al., 1998b; Gent et al., 1983; Hatchell et al., 1970; Miwa et al., 2004; Moehring and Rawls, 1970; Reisinger et al., 1988). Determination of appropriate regeneration and site preparation techniques requires coupling necessary ameliorative practices (Miwa et al., 2004) with knowledge of inherent site characteristics and silvicultural objectives (Zhao et al., 2009). Historically common site preparation practices include drainage, chopping, burning, disking, subsoiling, bedding, fertilization, herbicide application. Benefits provided by site preparation are improved aeration and nutrient availability to roots, competing vegetation control, additions of organic matter to surface horizons, control of logging slash distribution, and manipulation of soil physical and chemical properties (Lof et al., 2012; Miwa et al., 2004).

Drainage by ditching was previously practiced on wetland sites to improve growth of pine species by increasing available aerated soil volume (Allen and Campbell, 1988). Increases in pine site index from drainage have been estimated as 3 to 4.9 meters at base age 25 (Allen and

Campbell, 1988). In the Virginia coastal plain, Kyle et al. (2005) reported significantly taller loblolly pines in ditched treatments relative to bedded treatments when no fertilizer was applied. Existing drainages can be maintained, but construction of new drainage systems in jurisdictional wetlands is no longer a practical option due to permitting requirements of federal regulations.

Bedding, a more economically and legally feasible alternative to drainage, creates an elevated planting surface that can improve seedling survival and growth on wet sites by improving soil aeration, controlling competing vegetation, incorporating organic matter, and exposing mineral soil (Harms et al., 1998; Lof et al., 2012; Miwa et al., 2004; Reisinger et al., 1988). Hatchell (1981) reported survival and growth gains at age four in bedded plots relative to disked and non-mechanically prepared plots on poorly drained flats in South Carolina. A difference in growth on compacted and uncompacted bedded plots was not evident, suggesting that bedding mitigated the compaction. At age 12 years, the bedded plots still exhibited superior height and basal area (McKee and Hatchell, 1986). McKee and Wilhite (1986) observed the effects of bedding and fertilization on loblolly pine across a drainage gradient and found survival increases due to bedding at age 10 years were 7%, 19%, and 15 to 19% on moderately well drained, somewhat poorly drained, and poorly drained sites, respectively. Height gains due to bedding at age two were 33% and 18% on the moderately well drained and poorly drained sites, respectively, but gains diminished to seven percent more than controls by age 10 years on both sites. On poorly drained sites, heights remained 37 to 42% greater than controls through age 10. Aust et al. (1998a) reported that bedding successfully mitigated the damaging effects of compaction and rutting on loblolly pine survival and growth at age four in wet pine flats. Similarly, Eisenbies et al. (2004) documented greater biomass accumulation at age five on bedded sites than flat planted sites.

Growth gains as a result of bedding may diminish over time. Zhao et al. (2009) reported significant slash pine volume gains due to bedding until an age of 20 years on flatwoods spodosols. At stand age 33, Kyle et al. (2005) did not find significantly different productivity levels of loblolly pine among bedded, ditched, and chopped treatments. At the same site, bedded plots exhibited significantly greater productivity metrics than chopped only plots at age 21 years (Andrews, 1993). These declines in tree growth advantages with time on poorly drained sites likely occurred because non-bedded areas eventually develop sufficient evapotranspiration rates to lower the water table and overcome excess moisture limitations (Kyle et al., 2005).

Although bedding can provide advantages for tree growth, it may fail to restore or further deteriorate soil physical properties on a short term basis. Gent et al. (1983) measured soil physical properties pre-harvest, post-harvest and post-site preparation (shear, burn, chop, and bed) in the lower coastal plain of North Carolina. Bedding did not decrease bulk density, but decreased macroporosity and hydraulic conductivity at the soil surface. Aust et al. (1998b) reported significantly reduced hydraulic conductivity in non-trafficked, bedded plots relative to non-trafficked, non-site prepared plots. On trafficked plots, however, bedding increased macropore space compared to non-site prepared plots. Overall, research suggests that the greatest advantage to bedding is the creation of elevated planting surface microtopography that improves seedling survival by ameliorating excess moisture limitations (Aust et al., 1998b; Passauer et al., 2013).

The effect of bedding, and mechanical site preparation in general, on soil properties and tree growth beyond one rotation is not well documented, and may contradict first rotation results. Tiarks and Haywood (1996) observed a growth reduction in slash pine (*Pinus eliottii* Engelm.) at age 10 due to planting a second rotation on existing beds. During the first rotation of this study, bedding provided slight advantages for growth. It is speculated nutrients were preferentially exploited in beds during the first rotation, leaving behind a confined, nutrient deficient soil for the second rotation.

An alternative to creating continuous linear beds is bucket mounding which forms discrete, roughly circular mounds, intended to attain the same seedling growth advantages as bedding (Sutton, 1993). Bucket mounding may be preferable to bedding because installation does not require slash and stump removal. It is also favorable in areas of aesthetic concern because it mimics natural pit and mound microtopography common in forested wetlands (Londo and Mroz, 2001). In addition to overcoming adverse soil conditions in excessively wet or disturbed sites, bucket mounding is performed in boreal forests to increase soil temperature in the rooting zone (Sutton, 1993).

Disking has been implemented in attempt to alleviate compaction and rutting associated with forest harvesting. Disking is intended to mechanically loosen soil, incorporate organic matter, and expose mineral soil (Miller et al., 2004). On an upland soil in the North Carolina piedmont, Gent et al. (1984) reported successful restoration of bulk density and macroporosity in surface horizons as a result of disking. However, hydraulic conductivity was reduced by disking. On wetland sites, disking may be a much less effective method of mitigating damage to soil physical properties. Aust et al. (1998a) found that disking failed to improve surface bulk density, macroporosity, and hydraulic conductivity values in trafficked areas of a wet pine flat. Furthermore, disking significantly decreased macroporosity and hydraulic conductivity in non-trafficked areas. Essentially, disking the undisturbed soil created a puddling effect by eliminating macropores. McKee and Shoulders (1974) found no significant difference in soil redox potential, depth to water table, and total aboveground biomass of slash pine on disked and non-site prepared plots on medium to slowly drained soils in Louisiana. The study did not directly measure soil physical properties, but redox potential and depth to water table provide insight to soil aeration. In a study on a similar site, Mann and Derr (1970) also reported no significant height growth gains in slash pine at age eight years due to disking. However, disking increased loblolly pine heights by an average of 0.67 m at age eight years.

1.1.8 Summary of Literature Review

Forested wetlands provide ecologically and economically valuable services. Expanding human development enforces a need to conserve these services while maintaining timber management as a viable, sustainable option on wetland sites. However, the frequent high moisture content of forested wetland soils makes them particularly vulnerable to soil compaction and rutting under the forces applied by heavy machinery. Compaction and rutting have degrading impacts on soil physical properties which are controlling factors of wetland dynamics and function. Persistence of harvesting impacts on soil properties varies with site specific factors, and the potential for long term impairment validates implementation of ameliorative practices to speed the restoration of soil properties and wetland services.

1.1.9 Conclusions

Ideally, forested wetland timber harvesting should be scheduled to avoid high soil moisture conditions. However, this is logistically infeasible due to the prevalence of low lying terrain, long wet seasons, and limited wood storage capacities. Several studies have quantified the effect of harvesting soil disturbance and site preparation on tree growth over time, but few have maintained long term analysis of soil properties. The few long-term studies that have evaluated long term site preparation and traffic effects in wetlands invariably found that soil physical properties changed over time. Thus, it would be beneficial to re-evaluate site preparation and trafficking studies, while considering inherent site properties that may act as natural repair mechanisms. This may improve the ability to predict long term impacts on soil properties and tree growth, allowing forest management decisions to be made efficiently.

1.2 Objectives and Organization

This study has three main objectives. The first is to assess the 23 year effects of mechanical site preparation on loblolly pine productivity and soil properties. The second objective is to examine loblolly pine productivity and soil properties as influenced by wet weather primary skid trails at stand age 23 years. The final objective is to determine if soil properties and loblolly pine productivity in wet weather primary skid trails has naturally recovered to the state of an undisturbed soil. Chapter two will discuss soil properties as affected by site preparation, primary skid trails, and soil recovery mechanisms after 23 years. Chapter three will address loblolly pine growth as influenced by site preparation, primary skid trails, and productivity recovery at stand age 23 years. Chapter four will provide major conclusions and management implications based on the two manuscript chapters.

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2.0 SOIL PROPERTIES AND LOBLOLLY PINE (*PINUS TAEDA* L.) PRODUCTIVITY AS INFLUENCED BY WET SITE HARVESTING AND SITE PREPARATION AT STAND AGE 23 YEARS IN THE LOWER ATLANTIC COASTAL PLAIN.

2.1 Abstract

Forest harvesting equipment traffic may alter soil properties and reduce forest productivity if soil disturbances are not mitigated. Salvage logging operations were conducted during high soil moisture conditions on the South Carolina, USA coast to salvage timber and reduce wildfire fuel loads following Hurricane Hugo in 1989. Six long term study sites were established on wet pine flats to evaluate the 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, four levels of site preparation as the whole plot factor (bedding (Bed), disking with bedding (D/B), disking (Disk), no site preparation (None)), and two levels of traffic as the subplot factor (primary skid trail (On), no obvious traffic (Off)). A remeasurement of the original study established in 1991 was conducted in 2015 at stand age 23 years (25 years after salvage logging). 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 among treatments that resulted from 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 increased elevation of the bed surface above the water table and improved soil drainage. This implies greater aeration for roots, but trade-offs in above-ground 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 ($p = 0.1127$). Total soil nitrogen ($p < 0.0001$) was significantly lower in Bed and D/B treatments, likely due to enhanced plant availability and allocation in above ground biomass. Soil phosphorus ($p = 0.0002$) concentration varied significantly among site preparation treatments, but all values are considered deficient for loblolly pine growth. 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. This suggests that natural soil recovery mechanisms at the study sites were sufficient in mitigating the effects of wet site harvesting over the course of 23 years.

2.2 Introduction

2.2.1 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 et al., 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 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; Moerhing 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).

2.2.2 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.

2.3 Methods

2.3.1 Study Site Description

Six experimental sites were established within the Francis Marion National Forest in Berkeley County, South Carolina, United States (Figure 2.1). 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^{o}C during the summer and 15.5^{o}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; USDA NRCS 2016b). Each of these soils has a water table at or near the soil surface during some part of the year.

Figure 2.1. Approximate location of study area within the Francis Marion National Forest, Berkeley County, S.C., United States.

2.3.2 Experimental Design

The study was conducted as a split plot within an unbalanced randomized complete block design with 12 blocks based on geographic location and soils, four levels of site preparation as the main plot factor (bedding, flat disking, flat disking with bedding, and no site preparation), and two levels of traffic as the subplot factor (primary skid trail, no obvious disturbance) 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.

2.3.3 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) (Figure 2.2). Experimental unit subplots are each 24.4 x 6.1 m in size (Tippett, 1992). Detailed maps of subplot units within each site are provided in Tippet (1992). Loblolly pine seedlings from a local nursery were planted on a 2.0 x 0.6 m spacing (three rows in each subplot) in February 1992 and thinned to approximately a 2.0 x 1.8 m spacing in 1996 (Scheerer, 1994). Treatment combinations of the two unmeasured experimental units are On-Disk and Off-Disk.

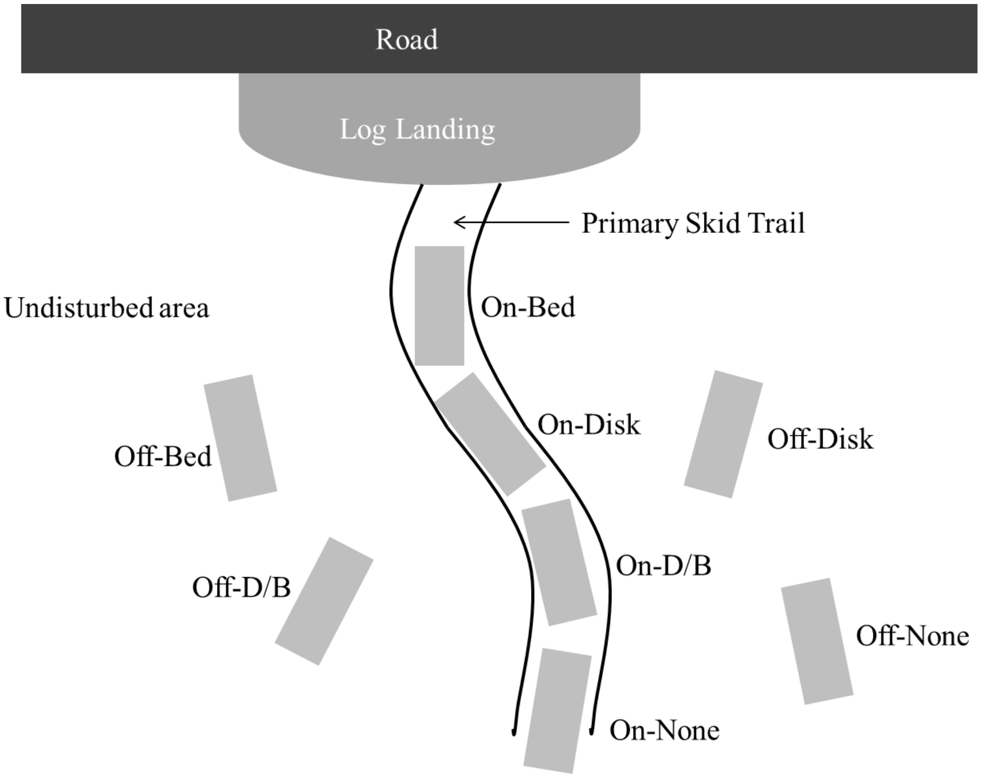

Figure 2.2. Generalized layout of treatment subplots within a block.

2.3.4 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 x 5 cm soil cores were systematically collected from the soil surface in each subplot experimental unit (Figure 2.3) 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}. Composite subsamples were systematically collected from the upper 15 cm of the soil profile using a push tube sampler (Figure 2.3) (Peterson 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 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 Gonzolez-Benecke et al. (2014). Green weights were approximated by multiplying the result of this equation by a factor of two. Stand density and green above-ground 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 Figure 2.3 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.

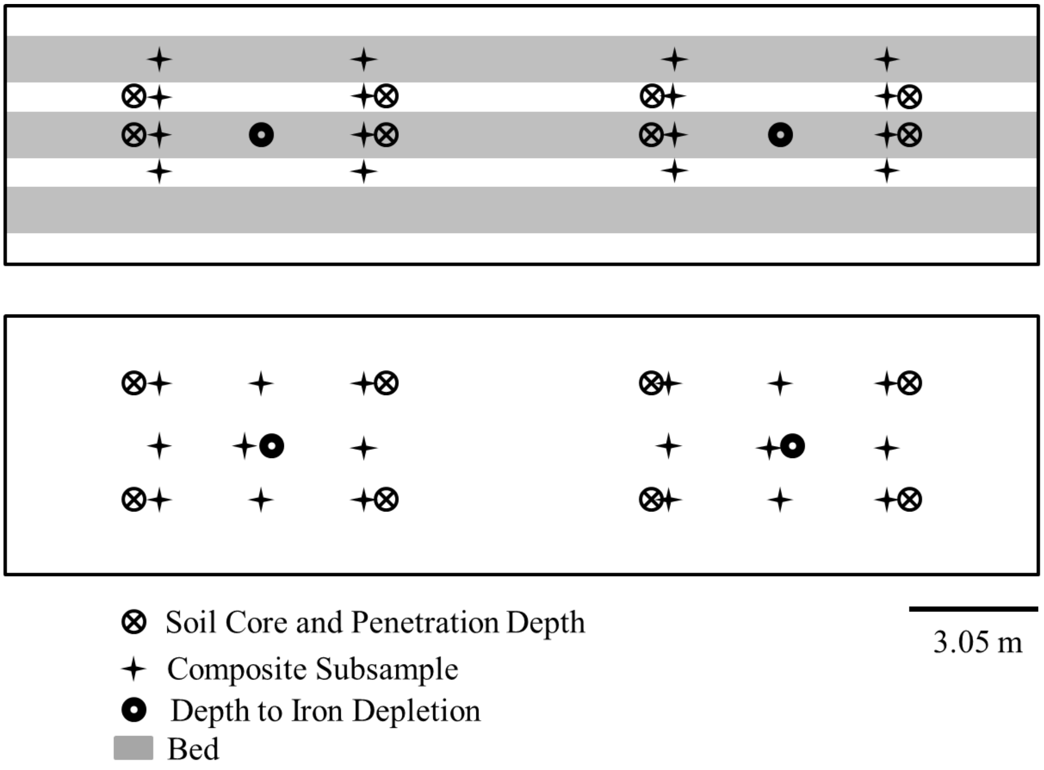

Figure 2.3. Schematic of systematic subsampling with Bed and D/B treatment subplots (top) and Disk and None subplots (bottom).

2.3.5 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).

2.4 Results

2.4.1 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.

2.4.2 Site Preparation

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. Disk and None also did not have significantly different bulk density. 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. Disk and None were also not significantly different. 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 None, but not Bed. Bed had significantly greater total porosity than Disk, but not None. Disk and None did not have significantly different total porosity. 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. Penetration depth of Disk and None was also not significantly different (Table 2.1).

Table 2.1. 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)

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 2.2). 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 2.3).

Table 2.2. 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.) (%)	Soil Depth to Iron Depletion (S.E.) (cm)
Bed	2.43 bc	753.87 a	2.17 a	39.95 a
	(0.12)	(50.94)	(0.13)	(2.56)
D/B	2.18 c	765.80 a	2.19 a	38.79 a
	(0.12)	(50.94)	(0.13)	(2.56)
Disk	3.02 a	1050.51 b	2.94 b	30.37 b
	(0.13)	(55.02)	(0.14)	(2.77)
None	2.66 b	1062.84 b	3.14 b	28.47 b
	(0.12)	(50.94)	(0.13)	(2.56)

Table 2.3. 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	1082.0 a	111.5 a
	(20.91)	(107.37)	(5.44)
D/B	243.2 a	1025.9 a	105.3 a
	(20.91)	(107.37)	(5.44)
Disk	129.8 b	516.8 b	95.3 a
	(22.59)	(115.79)	(5.87)
None	112.8 b	448.5 b	94.8 a
	(20.91)	(107.37)	(5.44)

2.4.3 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 2.4). Traffic had no significant effect on soil phosphorus (p = 0.1340), total soil nitrogen (p = 0.2589), of soil carbon (p = 0.2698) (Table 2.5). 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 2.6) 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 2.7). 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 2.7).

Table 2.4. 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	21.98 a	10.11 a	36.23 a	32.68 a
	(0.01)	(2.87)	(0.29)	(0.28)	(0.46)
On	1.42 b	20.49 a	10.08 a	36.08 a	29.72 b
	(0.01)	(2.91)	(0.29)	(0.28)	(0.47)

Table 2.5. LS mean values for soil chemical properties by traffic level. Values not followed by the same letter within a column are significantly different at $\alpha = 0.1$.

Traffic	Phosphorus (S.E.) (kg ha^{-1})	Total Nitrogen (S.E.) (μg g^{-1})	Carbon (S.E.) (%)
Off	2.46 a	889.15 a	2.66 a
	(0.10)	(22.43)	(0.05)
On	2.68 a	916.71 a	2.55 a
	(0.10)	(22.43)	(0.05)

Table 2.6. LS mean values for stand level parameters by traffic level. Values not followed by the same letter within a column are significantly different at $\alpha = 0.1$.

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	750.0 a	105.1 a
	(13.46)	(43.57)	(3.51)
On	179.1 a	791.5 a	97.7 a
	(13.46)	(43.57)	(3.51)

Table 2.7. 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

2.4.4 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 2.8), chemical properties (Table 2.9), and stand level metrics (Table 2.10) did not differ significantly between the Off-None and On-None treatment combinations.

Table 2.8. 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 hr^{-1})	Macroporosity (S.E.) (%)	Microporosity (S.E.) (%)	Total Porosity (S.E.) (%)	Penetration depth (S.E.) (cm)
Off-None	1.43	6.09	8.26	36.73	44.98	29.49
	(0.02)	(5.64)	(0.57)	(0.56)	(0.76)	(0.94)
On-None	1.43	19.36	9.28	36.90	46.17	27.26
	(0.02)	(5.92)	(0.59)	(0.56)	(0.79)	(0.98)
P-value	0.9279	0.1051	0.2121	0.8338	0.2763	0.1005

Table 2.9. 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.) (%)
Off-None	31.11	2.55	1016.02	3.16
	(3.02)	(0.18)	(50.68)	(0.12)
On-None	25.82	2.76	1109.65	3.13
	(3.02)	(0.18)	(50.68)	(0.12)
P-value	0.2169	0.4350	0.1933	0.8391

Table 2.10. 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	403.7	93.7
	(27.82)	(119.54)	(7.24)
On-None	119.8	493.4	96.0
	(27.82)	(119.54)	(7.24)
P-value	0.7209	0.5973	0.8259

2.5 Discussion

2.5.1 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 2.3) 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 2.1). 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 2.1) (Daddow and Warrington, 1983). The small differences in microporosity and total porosity values are also unlikely to affect pine productivity, 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 2.1). 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 2.1).

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 2.1). 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.

2.5.2 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 2.2). 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 2.1). 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 2.2). 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 2.3); 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 µg 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 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 concentrations in the Bed and D/B treatments are likely the result of greater soil aeration provided by these treatments (Table 2.2). 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 2.1) and depth to iron depletion (Table 2.2). 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 2.3), but Disk and None provide more long term carbon storage in soil (Table 2.2). 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 2.3). 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.

2.5.3 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 (Table 2.4, Table 2.5, Table 2.6, Table 2.7). 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 Daddow 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 three centimeters 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

(Table 2.8, Table 2.9, Table 2.10). 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.

2.6 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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3.0 LOBLOLLY PINE (*PINUS TAEDA* L.) PRODUCTIVITY 23 YEARS AFTER WET SITE HARVESTING AND SITE PREPARATION IN THE LOWER ATLANTIC COASTAL PLAIN

3.1 Abstract

Ground based timber harvesting on wet sites has been linked to alteration of soil properties that may result in reduced long term site productivity. Following Hurricane Hugo in the fall of 1989, numerous salvage logging operations were conducted under high soil moisture conditions to reduce wildfire risk and salvage timber within the Francis Marion National Forest in the lower coastal plain of South Carolina. Study sites were established on wet pine flats to examine the long term effects of primary skid trails and site preparation on planted loblolly pine (*Pinus taeda* L.) growth. Treatment effects were analyzed as a split-plot within a randomized complete block design with 12 blocks, four levels of site preparation (none, disking, bedding, disking with bedding), and two levels of machine traffic (primary skid trail, no obvious traffic). After 23 years, bedding and disking with bedding enhanced stand density ($p < 0.0001$) and above ground stand biomass ($p < 0.0001$) relative to the disking and non-site prepared treatments. None of the site preparation treatments were effective at increasing biomass of individual trees. Mean height ($p < 0.0001$), DBH ($p < 0.0001$), and biomass of individual trees ($p < 0.0001$) was lower on primary skid trails than in non-trafficked areas. Traffic did not have a significant effect on stand density ($p < 0.4662$) or stand biomass ($p = 0.1564$). Selected soil physical properties and productivity measurements were similar for the non-site prepared treatment on and off primary skid trails, suggesting that 23 years is sufficient time for soils in wet flats to naturally recover from wet weather harvest disturbance. This study indicates that bedding may be the most efficient management practice to enhance long term stand productivity on aeration limited sites by increasing seedling survival. Minimizing the spatial extent of skid trails may allow individual trees to have greater growth potential.

3.2 Introduction

3.2.1 Background

Forests are valued for providing a suite of ecosystem services, essential raw materials, and the foundation of the forest products industry. Globally, pressures on forest ecosystems are increasing due to population growth, conversion of forests to alternate land uses, and land degradation (Fox, 2000). Forest harvesting is typically executed with heavy machinery due to economic and operational efficiency (Miwa et al., 2004). Concerns regarding jeopardizing forest productivity via altering soil properties with ground based harvesting systems have been investigated extensively 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). Specifically, harvesting equipment traffic has been associated with increased bulk density, decreased macroporosity, and decreased hydraulic conductivity (Aust et al., 1995; Gent et al., 1983; Rab, 2004; Williamson and Neilson, 2000), increased soil strength (Hatchell et al., 1970; Lockaby and Vidrine, 1984); water table rise (Aust et al., 1993, 1995), and reduced organic matter content (Rab, 2004). These changes in soil properties have been linked to reduced tree survival and growth (Aust et al., 1998b; Moehring and Rawls, 1970; Naghdi et al., 2016; Murphy and Firth, 2004; Wert and Thomas, 1981).

Intensively managed forest plantations are essential to satisfy the global demand for forest products with current trends in population and land use (Fox, 2000). In the Southeastern United States, a substantial portion of plantation forest land is located on coastal plain wet flats, some of which are jurisdictional wetlands (Allen and Campbell, 1988; Harms et al., 1998; Stanturf et al., 2003). These forested wetlands provide a unique challenge to forest management because frequent high soil moisture conditions can accentuate the damaging effects of equipment traffic on soil properties and site productivity (Akram and Kemper, 1979; Greacen and Sands, 1980; Hatchell et al., 1970 Miwa et al., 2004; Moehring and Rawls, 1970). It is also desirable to maintain the host of ecosystem services provided by wetlands, in addition to those provided by forests, which are potentially jeopardized by forestry practices (Richardson, 1994). Although numerous forestry professionals have reported benefits of avoiding management practices involving heavy equipment under wet site conditions (Hatchell and Ralston, 1971; Miller et al., 2004; Moehring and Rawls, 1970; Reisinger et al., 1988), this is often not logistically or economically feasible (Miwa et al., 2004). The resulting alterations in soil properties that reduce site capability of supporting desired species must be mitigated in order to sustain long term forest productivity and ecosystem services (Burger, 2009). Some sites have natural mechanisms that allow sufficient long term recovery from the effects of soil disturbance such as sediment deposition, mixed clay minerology (McKee et al., 2012), high fertility, and weather patterns (Passauer et al., 2013). However, widely documented negative effects on soil properties and tree growth shortly after disturbance coupled with uncertainty of recovery potential justify implementation of site preparation as an ameliorative practice (Aust and Lea 1992; Eisenbies et al., 2004; Gent et al., 1983; Lof et al., 2012; Miller et al., 2004; Reisinger et al., 1988). Numerous site preparation techniques are available, and each method may provide a wide range of benefits that restore or enhance soil properties and productivity. Bedding is a commonly employed practice on poorly drained sites intended to increase the depth of aerated soil available to seedlings. Advantages in terms of soil physical properties and early tree growth as a result of bedding have been reported by Aust et al. (1998a), Eisenbies et al. (2004), and Hatchell (1981). Some research indicates that growth gains as a result of bedding diminish with time (Kyle et al., 2005; Wilhite and Jones, 1981; Zhao et al., 2009); however, long term effects of bedding on soil physical properties are not widely reported. Disking has been suggested as a method to alleviate equipment traffic induced compaction (Reisinger et al., 1988). Gent et al. (1984) concluded that disking was effective at restoring soil physical properties in the piedmont. In coastal plain studies, disking has significantly reduced macroporosity and saturated hydraulic conductivity (Aust et al., 1998b) and failed to improve slash pine (*Pinus elliotti*) growth (Mann and Derr, 1970; McKee and Shoulders, 1974).

Further research is needed to fully understand and predict the long term effects of wet weather harvesting disturbance and site preparation on soil properties and forest productivity on a site specific basis. Better ability to forecast these relationships through a rotation will allow forest management objectives to be satisfied more efficiently as the need for intensive forest management progresses (Fox, 2000).

3.2.2 Objectives

The objectives of this study are to assess the effects of site preparation and primary skid trails on loblolly pine (*Pinus taeda* L.) growth and selected soil physical properties at age 23 years. The study also seeks to determine if loblolly pine productivity and selected soil physical property values in primary skid trails have naturally recovered to the state of a comparable, undisturbed soil at stand age 23 years.

3.3 Methods

3.3.1 Study Site Description

Six experimental sites were previously established in Berkeley County, South Carolina within the Francis Marion National Forest (Figure 3.1). Berkeley County is in the lower Atlantic Coastal Plain physiographic province, and averages 129 cm of precipitation with hot summers and mild winters (NOAA, 2016).

Figure 3.1. Approximate location of study area in Berkeley County, South Carolina, United States.

The sites are classified as wet pine flats, characterized by minimal relief, dense argillic horizons, and a longleaf pine (*Pinus palustris* Mill.) and loblolly pine (*Pinus taeda* L.) dominated overstory. The sites were established in 1989 following the salvage logging of timber damaged by Hurricane Hugo to study the effects of wet weather primary skid trails and site preparation on soil physical properties and forest productivity (Scheerer, 1994; Tippett, 1992). Following the Hurricane, only five to 12 trees per hectare remained standing, thus the overstory removal was similar to a clearcut harvest. Common understory species include sweet pepperbush (*Clethra alnifolia*), inkberry (*Ilex galbra*), and sweetgum (*Liquidambar styraciflua*).

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; USDA NRCS 2016b). Each of these soils has a dense argillic horizon and a water table near the soil surface during some part of the year (USDA NRCS, 2016a).

3.3.2 Experimental Design

The experiment was conducted as a split-plot within an unbalanced randomized complete block design with twelve blocks consisting of four levels of site preparation main plot factor (bedding, disking with bedding, disking, and no site preparation) and two machine traffic levels as the subplot factor (primary skid trail, no obvious traffic). We were unable to relocate two of the original 96 subplot experimental units; therefore, a total of 94 subplot experimental units were included in this study.

3.3.3 Treatments

The six experimental sites (two blocks per site) were salvage logged with rubber tired skidders under high soil moisture conditions during the fall and winter of 1989. Subplots within each site are distributed across approximately eight to 12 hectares. Each subplot experimental unit is 24.4 x 6.1 m in size. The site preparation treatments are bedding (Bed), flat disking (Disk), flat disking with bedding (D/B), and no site preparation (None). Debris was removed from all plots using a Komatsu 65D bulldozer prior to treatment installation. Bedding treatments were installed with a Komatsu 65D bulldozer with a fire plow, and disking treatments were installed using a John Deere 400 bulldozer. Treatment installation was completed in September of 1991. Within each block, each site preparation treatment was installed on a primary skid trail (On) and in an area with no obvious traffic disturbance (Off) (Tippett, 1992) (Figure 3.2). Detailed maps of subplot experimental units within each site are provided in Tippet (1992). Loblolly pine seedlings were planted only within treatment plots on a 2.0 m x 0.6 m spacing (three rows in each subplot) in February of 1992 (Scheerer, 1994) and thinned to a 2.0 x 1.8 m spacing in 1996. The treatment combinations of the missing subplot experimental units are On-Disk and Off-Disk, and are in separate blocks.

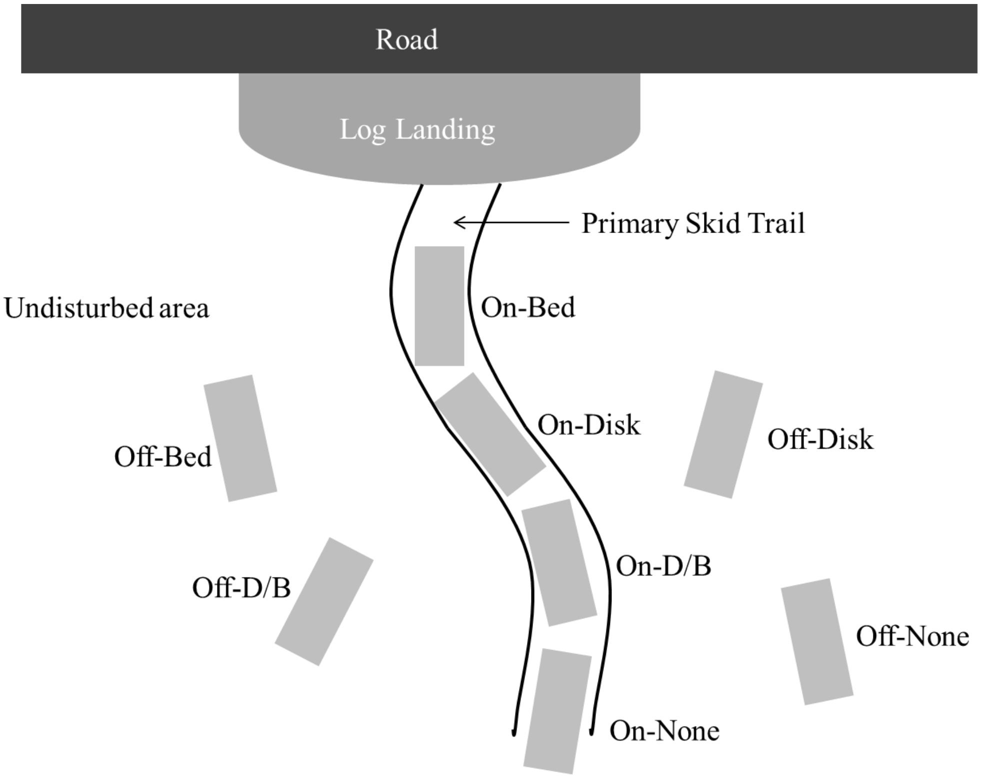

Figure 3.2. Generalized layout of treatment subplots within a block.

3.3.4 Data Collection

All field data collection and measurements were conducted during the summer of 2015 with the exception of approximately 130 soil cores which were compromised. These cores were collected during June of 2016. The total height and diameter at breast height (DBH) of all living loblolly pine trees within plots were measured. Total above ground dry biomass was calculated using an allometric equation provided by Gonzolez-Benecke et al. (2014). Green weight of biomass was approximated by doubling the result of this equation. Stand density and biomass per hectare were calculated by scaling the number of trees and total biomass per plot, respectively, to one hectare. Eight soil cores were systematically collected in each subplot experimental unit using a double cylinder hammer driven core sampler and sealed for later analysis of saturated hydraulic conductivity (Ksat) (Klute and Dirksen, 1986), macroporosity, (Danielson and Sutherland, 1986), and bulk density (Blake and Hartge, 1986).

3.3.5 Statistical Analysis

The main effects of site preparation and traffic were analyzed using standard two-way ANOVA procedures. The main effect of site preparation was applied only to biomass per hectare, stand density, bulk density, saturated hydraulic conductivity, and macroporosity due to treatment interactions. The main effect of traffic was applied to all responses. A one-way ANOVA with eight treatments (i.e. Off-Bed, Off-D/B, On-Bed) was used to analyze the effects of site preparation on height, DBH, and biomass per tree. This analysis was also used to compare the None site preparation treatments for both traffic levels. Appropriate transformations were performed for responses exhibiting non-parametric behavior. Fisher’s LSD with α = 0.1 was used for all multiple means separations. (Ott and Longnecker, 2010; Stefano, 2001). All analysis procedures were conducted using JMP Pro 13 statistical software (SAS Institute, Inc., 2016).

3.4 Results

The interaction of block and site preparation was significant for stand density ($p = 0.0002$), individual tree height ($p = 0.0001$), DBH ($p < 0.0001$) and individual tree green biomass ($p = 0.0004$), however; interaction plots indicate that these interactions were co-directional. All other block-treatment interaction was not significant. The interaction between site preparation and traffic was significant for individual tree height ($p = 0.0019$), DBH ($p = 0.0346$), and green tree biomass ($p = 0.0223$). Interaction plots for these variables indicate that traffic was masking the main effect of site preparation, so the traffic and site preparation treatment combinations were analyzed as eight different treatments.

Within the Off traffic level, Bed, D/B, and Disk had significantly greater heights than None, but were not significantly different from one another (Table 3.1). Disk had the greatest absolute values for DBH and individual tree biomass, and these values were significantly greater than D/B and None, but not significantly different from Bed. For the On traffic level, Bed had the greatest height and was significantly greater than Disk and None, but not D/B. D/B had the greatest average DBH, but no treatments were significantly different. Individual tree biomass was lowest for Disk, but was not significantly lower than None. Bed and D/B individual tree biomass values were significantly greater than Disk, but not None. It is also of interest to compare measurements for Off-None and On-None. For these treatment combinations, height, DBH, tree biomass, stand biomass, stand density, bulk density, Ksat and Macroporosity were not significantly different (Table 3.1, Table 3.2).

Table 3.1. LS Mean values for individual tree and stand productivity parameters analyzed as eight separate treatments. Values not followed by the same letter within a column are significantly different by Fisher's LSD at $\alpha = 0.1$.

Traffic Site Preparation	Height (S.E.) (m)	DBH (S.E.) (cm)	Tree Biomass Green Weight (S.E.) (kg)	Stand Biomass Green Weight (S.E.) (Mg ha^{-1})	Stand Density (S.E.) (No. trees ha^{-1})
Off					
Bed	16.0 a	19.9 ab	281.4 ab	274.1 ab	1009.1 a
	(0.25)	(0.45)	(14.31)	(27.82)	(119.54)
D/B	15.8 ab	19.2 bc	266.5 bc	276.7 a	1110.0 a
	(0.25)	(0.45)	(14.20)	(27.82)	(119.54)
Disk	15.8 ab	20.8 a	318.9 a	148.3 cd	458.2 b
	(0.40)	(0.73)	(22.87)	(29.23)	(125.60)
None	14.7 cd	18.7 bcd	244.7 bc	105.7 d	403.7 b
	(0.41)	(0.75)	(23.56)	(27.82)	(119.54)
On					
Bed	15.5 ab	18.2 d	241.8 c	257.6 ab	1154.9 a
	(0.24)	(0.43)	(13.58)	(27.82)	(119.54)
D/B	15.3 bc	18.5 cd	244.7 c	209.9 bc	941.8 a
	(0.26)	(0.48)	(15.01)	(27.82)	(119.54)
Disk	13.9 d	17.3 d	195.5 d	118.0 d	579.4 b
	(0.36)	(0.65)	(20.64)	(29.23)	(125.60)
None	14.7 c	18.3 cd	234.4 cd	119.8 d	493.4 b
	(0.37)	(0.68)	(21.30)	(27.82)	(119.54)
P-Value	<0.0001	0.0012	0.0011	<0.0001	<0.0001

Table 3.2. LS Mean values for selected soil physical properties analyzed as eight separate treatments. Values not followed by the same letter within a column are statistically different by Fisher's LSD at α = 0.1.

Traffic Site Preparation	Bulk Density (S.E.) (Mg m^{-3})	Ksat (S.E.) (cm hr^{-1})	Macroporosity (S.E.) (%)
Off			
Bed	1.36 c	43.59 a	12.23 a
	(0.02)	(5.64)	(0.57)
D/B	1.35 c	27.86 b	10.94 ab
	(0.02)	(5.64)	(0.57)
Disk	1.43 ab	10.49 cd	8.89 d
	(0.02)	(5.93)	(0.59)
None	1.43 ab	6.09 d	8.26 d
	(0.02)	(5.64)	(0.57)
On			
Bed	1.43 ab	25.93 b	10.61 bc
	(0.02)	(5.64)	(0.57)
D/B	1.38 bc	19.68 bc	10.84 b
	(0.02)	(5.64)	(0.57)
Disk	1.45 a	15.81 bcd	9.5 cd
	(0.02)	(5.71)	(0.57)
None	1.43 ab	19.36 bcd	9.28 cd
	(0.02)	(5.92)	(0.59)
P-Value	0.0106	0.0002	<0.0001

Despite significant interaction, the overall effect of traffic was significant on individual tree height ($p < 0.0001$), DBH ($p < 0.0001$), and green tree biomass ($p < 0.0001$). Mean values for these variables were lower for the On treatment. Traffic did not have a significant effect on green stand biomass ($p = 0.1564$) or stand density ($p = 0.4662$) (Table 3.3).

Table 3.3. LS Mean values for tree and stand productivity parameters by traffic level at α = 0.1.

Traffic	Tree Height (S.E.) (m)	Tree DBH (S.E.) (cm)	Tree Biomass Green Weight (S.E.) (kg)	Stand Biomass Green Weight (S.E.) (Mg ha^{-1})	Stand Density (S.E.) No. trees ha^{-1}
Off	16.0 a	19.0 a	266.2 a	199.2 a	750.0 a
	(0.17)	(0.28)	(9.18)	(13.46)	(43.57)
On	15.4 b	17.6 b	225.1 b	179.1 a	791.5 a
	(0.16)	(0.26)	(8.38)	(13.46)	(43.57)

Table 3.4. LS Mean values of selected soil physical properties by traffic level at α = 0.1.

Traffic	Bulk Density (S.E.) (Mg m^{-3})	Ksat (S.E.) (cm h^{-1})	Macroporosity (S.E.) (%)
Off	1.39 a	21.98 a	10.11 a
	(0.01)	(2.87)	(0.29)
On	1.42 b	20.49 a	10.08 a
	(0.01)	(2.91)	(0.29)

Bed and D/B treatments had significantly greater green stand biomass ($p < 0.0001$) and stand density ($p < 0.0001$) than Disk and None treatments, but were not significantly different from each other. Disk and None treatments were also not significantly different in terms of green stand biomass and stand density (Table 3.5).

Bulk density was significantly greater for the On treatment than the Off treatment ($p = 0.0862$) (Table 3.4). The effects of site preparation on bulk density were also significant ($p = 0.0226$). Disk had the highest bulk density, but was not significantly different from None. Bed had significantly lower bulk density than Disk, but was not significantly less than None. Bulk density for the D/B treatment was significantly less than None and Disk, but not significantly different from Bed (Table 3.5).

Table 3.5. LS Mean values for stand parameters and selected soil physical properties by site preparation treatment. Values not followed by the same letter within a column are significantly different by 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})	Bulk Density (S.E.) (Mg m^{-3})	Ksat (S.E.) (cm h^{-1})	Macroporosity (S.E.) (%)
Bed	265.8 a	1082.0 a	1.39 bc	34.76 a	11.42 a
	(20.91)	(107.37)	(0.02)	(4.41)	(0.44)
D/B	243.2 a	1025.9 a	1.36 c	23.77 a	10.89 a
	(20.91)	(107.37)	(0.02)	(4.41)	(0.44)
Disk	129.8 b	516.8 b	1.43 a	13.80 b	9.27 b
	(22.59)	(115.79)	(0.02)	(4.71)	(0.46)
None	112.8 b	448.5 b	1.42 ab	11.92 b	8.27 b
	(20.91)	(107.37)	(0.02)	(4.60)	(0.45)

After 23 years traffic did not significantly affect Ksat (p = 0.6144) or macroporosity (p = 0.9285) (Table 3.4). Bed and D/B had significantly greater Ksat (p = 0.0567) and macroporosity (p = 0.0071) than Disk and None, but are not significantly different from one another (Table 3.5). Disk and None also did not have significantly different Ksat or macroporosity. No significant interactions between traffic and site preparation were detected for bulk density, Ksat, and macroporosity.

3.5 Discussion

3.5.1 Site Preparation

The significantly greater stand density and stand biomass for Bed and D/B treatments in the current study reflects seedling survival trends on these sites at age four years. (Aust et al., 1998c) (Table 3.6). The most profound benefit of bedding that enhanced seedling survival may be the increase in aerated soil depth available to roots. Inadequate aeration is a common stressor to regeneration in wet pine flats (Allen and Campbell, 1988) due to destruction of macropore space via soil disturbance (Aust et al., 1993, 1995, 1998a, 1998b; Gent et al., 1983; Greacen and Sands, 1980; Moehring and Rawls, 1970) and water table rise resulting from decreased transpiration rates (Sun et al., 2000; Xu et al., 2002) and interruption of soil drainage via machine traffic (Aust et al., 1993, 1995). Within the On treatment at age four years, Aust et al. (1998b) reported macroporosity benefits as a result of Bed and D/B treatments. Macroporosity values for None and Disk remained well under the aeration porosity threshold of 10% for adequate root growth as suggested by Vomocil and Flocker (1961). Planting beds also reduce aeration deficits by providing seedlings with greater elevation above the water table (Xu et al., 2002). Sanchez et al. (2006) further exemplified aeration benefits of bedding by noting that bedding provided greater mean stand volume of loblolly pine at age 10 years on inherently wetter parts of a study area, but not areas without excess moisture. Additional potential benefits of bedding for seedling survival include incorporation of organic matter, exposure of mineral soil, compaction alleviation, and competing vegetation control (Harms et al., 1998; Hatchell, 1981; Lof et al., 2012; Miwa et al., 2004; Reisinger et al., 1988). The initially higher seedling survival rates within the Bed and D/B treatments are probably responsible for these treatments containing approximately double the stand density and stand biomass during the 24th growing season.

Table 3.6. Traffic and site preparation effects on height, DBH, and survival of loblolly pine at age four years and selected soil properties two years after treatment installation. Values within the same column not followed by the same letter are significantly different. Height, DBH, and Survival means from Aust et al. (1998c). Soil property means from Aust et al. (1998b). Means separation performed using Fisher's LSD at $\alpha = 0.1$* or $\alpha = 0.05^+$

Traffic Site Preparation	Height$^+$ (m)	DBH$^+$ (cm)	Survival$^+$ (%)	Bulk Density* (Mg m^{-3})	Macroporosity* (%)	Ksat* (cm hr^{-1})
Off						
Bed	2.7 a	2.4 a	85 a	1.25 a	14.3 c	2.9 bc
D/B	2.5 a	3.1 a	84 a	1.25 a	14.6 c	2.2 b
Disk	1.5 b	1.2 b	68 b	1.23 a	12.5 b	0.5 a
None	1.6 b	1.6 b	64 b	1.22 a	15.1 c	5.0 c
On						
Bed	2.5 a	3.0 a	87 a	1.29 b	13.3 bc	1.4 ab
D/B	2.3 a	2.7 a	82 a	1.34 b	9.9 b	0.5 a
Disk	1.5 b	1.1 b	71 b	1.38 b	2.7 a	0.5 a
None	1.4 b	0.9 b	66 b	1.33 b	2.6 a	1.0 a

Few other studies report long term stand density and stand biomass gains as a result of bedding as dramatic as this study. On a more fertile, intensively managed wet flat, Passauer et al. (2013) reported significantly greater loblolly pine stand density on wet harvested, bedded plots relative to wet harvested, flat planted plots at age 16 years, yet bedding only increased density by five percent. A significant difference in stand biomass was not detected. These moderate effects of bedding may be due to experimental controls to ensure survival through the first growing season, exceptionally dry growing seasons at ages 3-5, high soil fertility, or a combination of these factors (Passauer et al., 2013). Andrews (1993) reported that loblolly pine stand density values for bedded and control plots were not significantly different at age 21 in a Virginia wet flat. Stand volume per hectare was significantly greater at age 21 years on bedded plots, but not significantly different at age 33 years (Kyle et al., 2005). The persistent, dramatic response of stand density and stand biomass at the study sites contrasts the long term studies conducted by Andrews (1993), Kyle et al. (1995), and Passauer et al. (2013) indicating that trees respond to bedding in a site and condition specific basis as suggested by Fox et al. (2000) and Miwa et al. (2004).

Analyzing the effects of site preparation on individual tree height separately by traffic level revealed that the site preparation-traffic interaction for individual tree metrics was caused by varying responses to the Disk treatment. Disk has a positive effect on individual tree metrics relative to None for the Off traffic level. For the On traffic level, Disk has negative effects on individual tree metrics, although the effect is only significant for height (Table 3.1). It is speculated that the Off-Disk treatment incorporated organic matter into the soil profile (Miwa et al., 2004), providing a slowly available source of nutrients that benefitted individual tree growth relative to Off-None. On primary skid trails organic matter can be displaced (Rab, 2004), such that none is left behind to incorporate with site preparation.

Generally, the effects of Bed and D/B on individual tree metrics are very similar at age 23 years for both traffic levels. For the Off traffic level, the significant height advantage of Bed and D/B over none is likely the result of more favorable bulk density, Ksat, and macroporosity (Table 3.1, Table 3.2). For the On traffic level, only Bed provides significant height gains over None. It is surprising that D/B does not also result in significant gains, given its soil property similarities to Bed. At both traffic levels, neither Bed nor D/B provided a significant advantage in terms of DBH or individual tree biomass, probably due to the greater stand density of Bed and D/B. It is important to recall that Bed and D/B provided significant height and DBH advantages relative to Disk and None at age 4 years, although volume was not calculated and analyzed (Aust et al., 1998c) (Table 3.6). At age 23 years, the lack of significantly greater individual tree biomass coupled with only slight height advantages suggest that the growth of individual trees is following a type C response for Bed and D/B which connotes early growth gains that diminish with time (Morris and Lowery, 1988). This long term response type has also been reported in wet flats with loblolly pine in Virginia (Kyle et al., (2005) and slash pine in Florida and Georgia (Wilhite and Jones, 1981; Zhao et al., 2009). Relationships between water table elevations and transpiration rates likely contribute to the occurrence of this response. Water tables rise following harvest due to reduced transpiration rates (Sun et al., 2000; Xu et al., 2002) and soil disturbance (Aust et al., 1993, 1995) in forested wetlands, imposing excess moisture stress on seedlings. Bedding alleviates this issue for the early growth of seedlings. As seedlings become established and transpiration rates are restored on non-bedded sites, the excess moisture stress will eventually be overcome (Kyle et al., 2005). Additionally, trees may rapidly deplete nutrients that become concentrated in beds (Tiarks and Haywood, 1996) leading to rapid early growth that slows with time. Non-bedded plots are expected to have a more uniform distribution of nutrients and organic matter, and therefore, a more consistent growth rate through the rotation.

It is interesting that absolute bulk density values at stand age two years (Aust et al., 1998b) are lower than values based on stand age 23 year measurements. It is likely that organic debris and litter was left on site after salvage logging. Incorporation of this organic matter into subsamples would have resulted in lower bulk density. Over time, a portion organic matter may have oxidized, allowing mineral soil particles to settle into a smaller volume. There may also be a similar influence of soil settling in the Bed and D/B treatments. Differences in systematic subsample collection are probably another contributing factor to the apparent increase in bulk density.

At age 23 years, the study indicates that bedding and disking with bedding greatly enhance the amount of biomass accrued in a stand, likely due to greater initial survival, but no site preparation appeared to be advantageous for the biomass of individual trees. Disking with bedding shows no significant advantages to bedding in terms of individual tree growth, stand measurements and selected soil physical properties, yet is more expensive to implement. Thus, bedding is recommended as the most cost-effective method to ensure adequate survival, increasing long term stand productivity in disturbed or undisturbed soils when excess moisture is a stressor to survival early in the rotation.

3.5.2 Traffic

It is not surprising that skidder traffic on primary skid trails reduced the mean individual heights, DBH and biomass of loblolly pine (Table 3.3). Numerous researchers have documented reduced individual tree metrics in skid roads and harvest areas disturbed by heavy equipment under wet and dry trafficking conditions (e.g. Carter et al., 2006; Lockaby and Vidrine, 1984; Moehring and Rawls, 1970; Murphy et al., 2004; Naghdi et al., 2016; Wert and Thomas, 1981). In contrast to this study, several others have shown decreased metrics of whole stand productivity as well (Hatchell et al, 1970; Lockaby and Vidrine, 1984; Murphy and Firth, 2004; Wert and Thomas, 1981). Conclusions of reduced stand productivity from Hatchell et al. (1970) and Lockaby and Vidrine (1981) were made at stand age one and five years, respectively. These time periods are probably not long enough to constitute a soil recovery period, although both are coastal plain sites. Decreased stand volume has been reported to persist through ages 21 and 37 by Murphy et al. (2004) in New Zealand and Wert and Thomas (1981) in Oregon, United States, respectively. Both of these studies have inherently different climate and soils than the study sites, and therefore would be expected to recover differently. Additionally, treatments in Murphy et al. (2004) incorporated intentional topsoil and litter removal which may have exacerbated the effects of compaction. Results of this study were found to be consistent with those of Sanchez et al. (2006) on similar soils in North Carolina. Stand volume was not significantly decreased by intentional compaction; however absolute values decreased as compaction intensity increased.

Reduction in tree growth and stand productivity following harvest related disturbance, particularly on wet sites, is typically linked to increased bulk density, decreased macroporosity, and decreased hydraulic conductivity (Aust et al., 1998b; Gent et al., 1983; Lockaby and Vidrine, 1981; Moehring and Rawls, 1970; Reisinger et al., 1988). Bulk density, macroporosity, and Ksat in On plots have generally recovered to values similar to Off plots, despite being substantially altered following disturbance (Aust et al., 1998b). The only soil property remaining significantly different by traffic is bulk density, which is only 0.03 Mg m^{-3} greater for the On treatment. This small difference in bulk density is unlikely to have a substantial influence on tree growth, and the value of 1.42 Mg m^{-3} (Table 3.2) is below the generally accepted root limiting bulk density for the surface texture of all soil series in the study sites (Daddow and Warrington, 1983). The recovery of soil properties degraded by wet weather harvesting is consistent with the conclusions of Lang et al. (2016) after 17 years. Despite these soil property similarities, individual tree metrics in the On plots remain inferior to those in Off plots, perhaps because they were subjected to more stressful growing conditions during the time required for soil properties to recover. This result contradicts the conclusion that wet weather harvesting is generally not harmful to loblolly pine growth at age 16 drawn by Passauer et al. (2013). This may be because measurements by Passauer et al. (2013) were taken across the entire harvest area, representing lower traffic intensity than primary skid trails alone. The higher stand density of On offsets the lesser individual tree biomass such that stand biomass is not significantly different by traffic level. It is unclear if the difference in stand density is the cause or effect of individual tree biomass. However, stand density is not significantly different by traffic, reflecting the trend in survival at age four years (Aust 1998b, 1998c) (Table 3.6).

3.5.3 Recovery of Primary Skid Trails

Four years after wet weather harvest, bulk density was significantly greater while macroporosity and Ksat were significantly lower for On-None than Off-None. Likewise, seedlings had significantly lesser heights and diameters through age two years for On-None than Off-None (Aust et al., 1998b). At stand age 23 years, the similar values for Off-None and On-None for all measurements suggest that skid trail soil property and productivity levels have recovered to the state of an undisturbed soil without site preparation. Natural soil recovery mechanisms active at the sites include wet-dry cycles, bioturbation by soil fauna, and rooting activity. Shrink-swell potentials are generally low at the sites and minerology is dominantly siliceous (Long, 1980). Wet-dry cycles accelerate aggregate formation while soil fauna and rooting activity form voids in soil and incorporate organic matter. Each of these mechanisms could potentially contribute to advantages associated with increased macroporosity and decreased bulk density (Larson and Allamaras, 1971, Miwa et al., 2004). It is possible that wet-dry cycles had substantial influence on recovery due to frequent observation of cyclic ponding and dry-down that occurred while field work was in progress. Abundance of active soil-burrowing organisms was confirmed during data collection. The efficacy of natural recovery mechanisms at these sites implies that site preparation is not necessary to restore soil and vegetative productivity of primary skid trails to a level comparable to undisturbed soils in the long term. Natural recovery of site productivity at stand age 16 years (Passauer et al., 2013) and soil properties 17 years post-treatment (Lang et al., 2016) was reported on a similar, but more fertile site with greater shrink-swell potential. Rab (2004) found the deleterious effects of primary skid trails on macroporosity and bulk density to be persistent through ten years in an upland setting. This may suggest that natural recovery mechanisms are more effective in wet flats, perhaps due to cyclic hydrologic fluxes. Additionally, high bulk density limitations may be more easily ameliorated by rooting activity in wetlands, because mechanical resistance to root growth is inversely correlated with soil moisture (Busscher et al., 1997). It is also speculated that forest productivity recovered, in part, due to the ability of roots to grow outside of skid trails within a few years of planting (Aust et al., 1998b). This would have diminished the impact of reduced growth as a result of impaired soil physical properties that persisted within skid trails for at least the first few years after planting.

3.6 Conclusions

At these sites, bedding and disking with bedding were effective site preparation treatments to greatly enhance loblolly pine stand productivity, but not individual tree growth parameters at age 23 years. Stand productivity was increased due to greater seedling survival for bedding and disking with bedding treatments. Bedding is a more efficient management practice than disking with bedding because both treatments provide similar soil properties and vegetative productivity, but disking with bedding is more expensive. Ensuring sufficient seedling survival is the foremost critical challenge forest managers encounter when establishing a stand.

Management practices intended to improve tree growth may be a fruitless allocation of resources if initial seedling survival is poor. Therefore, it is recommended that bedding be implemented in intensive plantation forestry where poor soil aeration may threaten regeneration of an adequately stocked stand. When all site preparation treatments are considered, rubber-tired skidder trafficking during wet weather decreased individual tree growth parameters, despite apparent long term recovery of selected soil physical properties. It is a commonly recommended best management practice to avoid wet-weather operations and limit the spatial extent of soil disturbance in order to prevent soil and productivity degradation. Results of the study support this practice. Site preparation is not necessary, if it is strictly intended to restore primary skid trail soil properties and vegetative productivity levels to those of undisturbed, non-site prepared soils for these sites. The natural repair mechanisms for these particular forested wetlands were adequate over the course of 23 years.

3.7 Acknowledgements

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4.0 CONCLUSIONS

Bedding and disking with bedding were effective mechanical site preparation treatments to enhance soil properties and loblolly pine (*Pinus taeda* L.) stand productivity on coastal plain wet flats through stand age 23 years. Disking did not provide appreciable long term advantages for loblolly pine stand productivity or soil properties relative to non-site prepared soils. All site preparation treatments performed similarly in terms of individual tree metrics. The bedding and disking with bedding treatments contained approximately twice the stand density and stand biomass than the disking and non-site prepared treatments. This was probably due to increased seedling survival that resulted from aeration benefits of bedding, as evidenced by macroporosity values, the soil surface elevation relative to a water table, and depth to iron depletion. The initial soil property and stand density benefits of bedding and disking with bedding likely promoted greater rooting activity, which slightly decreased bulk density and increased saturated hydraulic conductivity over time relative to the disking and non-site prepared treatments. Nutrient availability and plant uptake may have also been improved by bedding and disking with bedding. Bedding and disking with bedding store more carbon in above ground tree biomass, but less in soil than disking and non-site prepared treatments. These differences balance so that the total amount of carbon stored in soil and above ground loblolly pine biomass is similar among treatments. Overall, the study indicates that bedding is an effective method to overcome insufficient soil aeration to ensure acceptable seedling survival, enhance long term stand productivity, and create favorable soil properties for loblolly pine growth on coastal plain wet flats. Bedding is a more efficient site preparation technique than disking and bedding because both produce similar soil properties and productivity levels, yet disking and bedding requires additional treatment. Achieving adequate seedling survival is the primary challenge encountered by forest managers when regenerating a stand. Failing to address site factors that limit survival may result in long term productivity and ecosystem function losses.

Whether considering all site preparation levels or only non-site prepared treatments, soil property differences between primary skid trails and non-trafficked soil were minimal at stand age 23 years, despite being altered after harvest. This suggests that natural soil recovery mechanisms were sufficient in restoring degraded soil properties in primary skid trails. Mechanisms that may have contributed to soil recovery include wet-dry cycling, rooting activity, and bioturbation by soil fauna. Stand biomass and density were also similar among traffic levels, with and without site preparation. However, when all levels of site preparation are considered, individual tree measurements were reduced by primary skid trails through age 23 years. This is probably because trees in skid trails were subjected to a more stressful soil environment during the period of time required for soils to recover. The long term reduction in tree size implies that product value may be lost within primary skid trails. This emphasizes the importance of minimizing the spatial extent of timber harvest traffic, as suggested by best management practices. Sites with less effective recovery mechanisms may have greater potential for sustained productivity loss. For non-site prepared soils, individual tree and stand parameters were similar on primary skid trails and non-trafficked soils. Thus, site preparation may not be required to ameliorate soil properties and forest productivity on wet weather primary skid trails in coastal plain wet flats similar to our research sites, but site preparation such as bedding may be necessary to overcome inherently poor aeration and ensure adequate initial survival of planted seedlings and subsequent stand volume.

5.0 APPENDICES

5.1 Appendix A. Approximate Coordinates of Tagged Subplot Corners.

Subplot No.	Latitude	Longitude
1	33.109503	-79.700447
2	33.109129	-79.700405
3	33.109289	-79.700015
4	33.109013	-79.699720
5	33.109006	-79.699930
6	33.108816	-79.699927
7	33.109259	-79.700011
8	33.108630	-79.699549
9	33.108567	-79.699259
10	33.109405	-79.700366
11	33.108424	-79.699515
12	33.108151	-79.699228
13	33.108247	-79.698955
14	33.107770	-79.699203
15	33.107718	-79.699189
16	33.107017	-79.699336
17	33.113987	-79.701243
18	33.113640	-79.701793
19	33.113637	-79.701501
20	33.113266	-79.701638
21		
22	33.113126	-79.702032
23	33.113731	-79.701816
24	33.113428	-79.702362
25	33.113532	-79.702711
26	33.113438	-79.703056
27		
28	33.113991	-79.703019
29	33.113310	-79.702043
30	33.113918	-79.702373
31	33.114037	-79.702080
32	33.113849	-79.702035
33	33.118544	-79.712130
34	33.118310	-79.712365
35		
36	33.117610	-79.712577
37	33.117308	-79.712121
38	33.117086	-79.712026
39	33.116661	-79.711729
40	33.118105	-79.711447
41	33.118196	-79.711273
42	33.118485	-79.710907
43	33.118216	-79.709985
44	33.117634	-79.710453
45	33.119082	-79.711288
46	33.118732	-79.711401
47	33.118698	-79.711570
48	33.118803	-79.711840
49	33.140467	-79.694671
50	33.140556	-79.695235
51	33.141376	-79.694924
52	33.141428	-79.694854
53	33.141648	-79.694406
54	33.141587	-79.694475
55	33.141877	-79.695319
56	33.141910	-79.695605
57	33.142072	-79.696027
58	33.142574	-79.695755
59	33.142303	-79.695658
60		
61	33.142612	-79.694427
62	33.142608	-79.264297
63	33.142775	-79.693942
64		
65	33.137545	-79.671047
66	33.137697	-79.671369
67	33.138112	-79.672257
68		
69	33.139080	-79.675244
70	33.138944	-79.675295
71	33.139461	-79.975608
72	33.139052	-79.675729
73	33.138636	-79.675614
74	33.138515	-79.675722

Subplot No.	Latitude	Longitude
75	33.138575	-79.675993
76	33.139479	-79.676714
77	33.139243	-79.676278
78	33.139216	-79.976050
79	33.139494	-79.675951
80	33.139273	-79.675890
81	33.214897	-79.649894
82		
83	33.214980	-79.650044
84	33.214766	-79.650040
85	33.214491	-79.650608
86	33.214486	-79.650716
87	33.214495	-79.650692
88	33.217068	-79.650982
89	33.217125	-79.651229
90	33.217060	-79.650961
91	33.216672	-79.651290
92	33.216694	-79.651495
93	33.216088	-79.650899
94	33.216029	-79.650744
95	33.216075	-79.651016
96	33.216216	-79.651238

Detailed maps that indicate subplot numbers and tagged corners are provided in Tippet (1992).

Coordinates were taken with recreation grade handheld GPS and are subject to error. Blank lines indicate the subplot was not re-located or obvious GPS error.

5.2 Reference

Tippett, M.D. 1992. Impacts of timber harvesting on soil physical properties in wetlands. M.S. thesis, Dep. of For., VPI&SU, Blacksburg, VA. 165 p.