CHAPTER I
INTRODUCTION

Southern pine forests are highly productive forest systems. Southern pine species, which include loblolly pine (*Pinus taeda* L.), shortleaf pine (*P. echinata* Mill.), longleaf pine (*P. palustris* Mill.), slash pine (*P. elliottii* Engelm.), and Virginia pine (*P. virginiana* Mill.), accounted for about 28% of the United States' softwood growth in 1992 (net volume) (Powell et al., 1993). Of the southern pines, loblolly pine was the most-planted tree species (in acreage) in the United States because of its high productivity and wide range of adaptability. The Southeastern Lower Coastal Plain loblolly pine plantations are one of the most productive forest systems in the United States (Allen and Campbell, 1988). The site indices of these forests often exceed 25 m in 25 years, which is considered highly productive. Forest industries have made tremendous capital investments in these productive pine forests to ensure that they have the quantity, quality, and timed delivery of wood fiber.

Intensively managed loblolly pine plantations established on wet pine flats[1] are often harvested under wet conditions. Industrial forest managers are concerned about three potential impacts of harvesting under these conditions: (1) potential reductions in long-term site productivity, (2) potential alteration of ecosystem functional processes in jurisdictional forested wetlands (areas that fall within the jurisdiction of the Federal Water Pollution Control Act of 1972 and its amendments), and (3) potential non-compliance with industry-supported initiatives such as Forestry Best Management Practices (BMPs) and the Sustainable Forestry Initiative (SFI).

Southern Pine Plantation Forests

Maximum production of wood, full utilization of forest resources, sustainable management of forests, and preservation of forest ecological functions are critical tasks for industrial forest resource managers. The demand for forest products has increased steadily in the United States since World War II. Domestic forest product production increased 60% between 1950 and 1992 (from 3 billion m^3 to 5 billion m^3) to meet the demand (Powell et

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[1] Wet pine flats are pine-dominated, poorly drained, broad plain wetlands in the Southeastern Lower Coastal Plain (Stout and Marion, 1993; Harms et al., 1998).

al., 1993). However, the increase of industrial forestland during the same period was only 16% (from 23.9 million hectares to 28.5 million hectares). Although other forests, such as national forests and non-industrial private forests, have contributed to wood production, this unbalanced increase of supply and demand for softwood products has increased the pressure on industrial forestlands, especially since the late 1970's. This might be partially responsible for the 1% decline of softwood growing stock that was detected between 1987 and 1992 in the South.

Currently, most forest industries in the southeastern United States acquire 50 to 100% of their wood fiber needs from non-fee lands, such as non-industrial private forests or publicly owned forests. Many forest industries own fee lands in order to ensure that they have greater control over their fiber supply, to ensure that they have sites that they can harvest during wet conditions, and to minimize the impacts on altered public policies regarding harvest of public lands. The ownership of forestland allows forest industry to manage it more intensively and for more specific products than is feasible on most non-industry land.

Proper silvicultural practices on pine plantations could significantly increase wood production. Comparison of average annual stand production between managed and unmanaged natural loblolly pine stands on a moderately productive site in southern Arkansas (Baker and Bishop, 1986) showed that the managed stands produced three times as much wood as did the unmanaged stands (6.8 m^3 ha^{-1} yr^{-1} and 2.2 m^3 ha^{-1} yr^{-1}, respectively). The other comparison indicated that mean annual yield of a 30-year-old, intensively managed, loblolly pine plantation was 10 m^3 ha^{-1}, whereas mean annual yield of a 40-year-old, natural, even-aged loblolly pine stand on average site (SI_{50} = 27 m) was 8 m^3 ha^{-1} (Baker and Langdon, 1990).

Environmental Issues Regarding Pine Flatwood Forests[2]

. The Southeastern Lower Coastal Plain flatwood sites (also known as wet flats, pine savannas, pine barrens, pocosins, bays, and pitcher plant flats) consist of relatively flat, poorly-drained areas. Most of these wetlands are classified as headwater systems within a

[2] Pine flatwoods include broader wetland and non-wetland forests in the South, of which pine is a major overstory component (Stout and Marion, 1993; Harms et al., 1998).

regional hydrologic system, since flatwoods generally do not receive floodwater from adjacent areas. Therefore, soil water saturation in this system is produced by precipitation and slow drainage due to the flat topography and impermeable soil clay layers in the soil profile (episaturation).

Many flatwoods are sufficiently wet to meet the jurisdictional criteria for forested wetlands (Stout and Marion, 1993, Harms et al., 1998). Much of the native pine and hardwood stands of the flatwoods have been converted to pine plantations, agricultural lands, industrial developments, and residential areas. Earley (1990a) reported that about a third of the flatwoods in North and South Carolina had been drained and developed, another third had been partially drained, and the remaining third was natural forest.

Drainage of flatwoods for development and agriculture is believed to disturb the functions and biological processes of the wetland systems. Conversion of the flatwoods to pine plantations may also affect the surrounding ecosystems (Earley, 1990a). Rapid drainage of surface and perched subsurface water from a naturally infertile sandy surface soil may increase soil nutrient losses. The drainage may also lower soil pH, and the lower pH may cause additional nutrient transformations and further nutrient losses. Drainage may increase water velocities in streams and increase suspended sediments, which may change stream aquatic communities. Increased water discharge may also dilute tidal marsh salinity and cause a habitat shift for salinity-sensitive organisms. Forest fragmentation resulting from artificial drainage networks and development may cause habitat loss for black bear and neotropical migratory birds that require large tracts of continuous, mature forest.

Pine plantations are generally considered to be one of the best alternative land uses for the flatwoods (Earley, 1990b). Unlike the other alternatives, common pine plantation silvicultural management practices, which include partial drainage and bedding site preparation, usually do not change the jurisdictional wetland status, although silvicultural practices may alter some of the wetland functions. However, the functional differences between undisturbed flatwoods and converted pine plantation forests are unknown, and the influence of the plantations on the surrounding environment is uncertain.

Concerns Regarding Long-Term Forest Productivity

Powers et al. (1990) reviewed several long-term forest productivity studies around the world and concluded that modern silvicultural practices, which include short rotations, monoculture plantations, and intensive use of heavy machinery, may decrease long-term forest productivity. Examples of declines in long-term productivity include Norway spruce (*Picea abis* (L.) Karst) in Europe (Krauss et al., 1939, Holmsgaard et al., 1961), radiata pine (*Pinus radiata* D. Don) plantations in Australia (Keeves, 1966), and Scots pine (*P. sylvestris* L.) in eastern Germany (Wiedemann, 1935). These forest productivity decreases were caused by soil compaction-induced drainage problems and/or organic matter removal and nutrient deficiencies.

In the United States, productivity declines related to forest harvesting operations have also been reported in the Southeastern Coastal Plain pine-flatwoods area. Gholz and Fisher (1983) estimated that the growth rate of the original over-100-year-old longleaf pine was almost twofold the productivity level of current slash pine plantations. They speculated that organic matter removals during harvesting and site preparation operations used during establishment of pine plantations caused productivity decreases in typical flatwood soils (Typic and Ultic Haplaquods).

Productivity Issues Regarding Intensively Managed Forest Plantations

Plantation forest operations such as timber harvesting, site preparation, planting, and thinning use heavy machinery in order to maximize economical and operational efficiencies. However, the use of heavy equipment has become a major concern among natural resource managers and environmental conservationists since the 1960's because the heavy equipment disturbs the forest floor, especially during moist and wet soil conditions. Garrison and Rummell (1951) evaluated soil disturbance areas for different logging methods and found that cable and tractor logging disturbed larger areas (30% and 26%, respectively) than horse logging (17%). Twenty-six percent of the total logging area was severely disturbed by tractor skidding (Steinbrenner and Gessel, 1955).

Many research studies have evaluated the effects of soil disturbance and organic matter removal on seedling survival and growth (Pearson and Marsh, 1935; Youngberg, 1959; Perry, 1964; Moehring and Rawls, 1970; Hatchell et al., 1970; Simmons and Ezell, 1983; Lockaby and Vidrine, 1984; Scheerer et al., 1994; Campbell, 1978; Reisinger et al., 1988). Generally, these researchers have concluded that forest harvesting, especially during wet weather, altered soil properties and negatively affected seedling growth. Logging operations conducted on clay-textured soils under wet conditions reduced water and air permeability of the soil, thus creating adverse soil conditions for seedling growth (Pearson and Marsh, 1935). Youngberg (1959) reported that significant increases of bulk density and decreases of organic matter in the surface 0-30 cm on crawler tractor trails reduced soil aeration and created nitrogen deficiency. Survival percentages of subsequently planted Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedlings were not affected, but seedling height within the crawler tractor trails was significantly lower than that within uncompacted soils.

Perry (1964) evaluated water infiltration rate and tree growth response in loblolly pine plantations and found that water infiltration in 26-year-old ruts was significantly lower than that outside of ruts. He also noted that tree heights, diameters, and volumes in the rutted areas were lower than in non-rutted areas. Moehring and Rawls (1970) observed that heavy equipment traffic disturbances of the forest floor include organic matter loss and soil compaction on the drier sites and organic matter loss and soil compaction, puddling, and smearing on the wetter sites. They found that thinning operations under wet weather increased bulk density from 1.24 g cm^{-3} to 1.40 g cm^{-3}, and loblolly pines that were compacted on three to four sides of their rooting area had decreased diameter growth. Harvest-induced rutting was reported to have similar negative effects on diameter growth of thinned natural loblolly pine on the Arkansas coastal plain (Powell, 1993).

Hatchell et al. (1970) evaluated the growth response of naturally regenerated loblolly pine seedlings on disturbed soils in the lower coastal plain of South Carolina and Virginia. They found that soil physical properties on primary skid trails and logging decks were altered, especially in low-lying wet areas, and pine seedling growth in the disturbed areas was severely retarded. Simmons and Ezell (1983) evaluated the effect of tractor passes on soil physical properties and subsequent loblolly pine seedling survival and growth responses. They found that surface soil bulk density increased about 10% after the first tractor pass, but the second pass only increased the bulk density by an additional 1%. Seedling survival and root growth were decreased in the one- and two-pass compacted loamy sand soils and two-pass compacted sandy loam soils.

An evaluation of the response of directly-seeded loblolly pine to different soil disturbance levels such as primary and secondary skid trails and logging decks in northeastern Louisiana fine loamy soils (Lockaby and Vidrine, 1984) concluded that soil disturbances decreased seedling growth, especially in the primary trails and logging decks. A comparison of two-year-old planted loblolly pine seedling growth within rutted and undisturbed sites in wet pine flats in South Carolina revealed higher mortality and lower seedling growth in the rutted sites, regardless of site preparation (Scheerer et al., 1994). The rutting had negative consequences for seedling survival and growth because it decreased site drainage and aeration.

Campbell (1978) used soil survey data to estimate the effects of wet- and dry-weather harvesting on loblolly pine site indices for different soil textures and moisture levels. The overall conclusion was that wet-weather harvesting decreased site indices (SI_{50}) by 1.5 to 3 m within all soil texture classes. In a review of the effects of heavy machine harvesting on soil properties and seedling growth in the South, Reisinger et al. (1988) concluded that most of the studies had shown negative effects on soil properties, including higher bulk density and soil strength and lower total- and macroporosity, infiltration, and saturated hydraulic conductivity. The altered soil physical properties decreased seedling root growth and overall site productivity.

Results from field experiments were corroborated by several greenhouse experiments. Foil and Ralston (1967) tested loblolly pine seedling growth response to experimentally compacted sandy, loamy, and clayey soils. They observed that root lengths decreased when macroporosity was reduced less than 10%, and when sandy and loamy soils were loosened and contained very high macroporosity. Mitchell et al. (1982) conducted a similar loblolly pine growth response study of different levels of compaction on a typical sandy loam Piedmont surface soil. They found that seedling root mass decreased linearly as bulk density increased from 1.2 to 2.0 g cm^{-3}, and root absorption capacity decreased significantly when the bulk density exceeded 1.4 g cm^{-3}.

Intensive management of short-rotation pine plantations could remove substantial nutrients from a forest system. Jorgensen and Wells (1986) found that whole-tree harvesting of 16- and 32-year-old loblolly pine stands decreased total site nitrogen by approximately 136 kg ha^{-1} (or 8.5 kg ha^{-1} yr^{-1}) and 204 kg ha^{-1} (or 6.4 kg ha^{-1} yr^{-1}), respectively, whereas stem-only harvesting of 16-year-old stands increased total site nitrogen 6.7 kg ha^{-1} (or 0.4 kg ha^{-1} yr^{-1}) due to nitrogen fixation and atmospheric input, and 32-year-old stands decreased 9 kg ha^{-1} (or 0.3 kg ha^{-1} yr^{-1}).

Forest harvesting operations often release available nitrogen from the soil nitrogen pool (Binkley, 1984; Burger and Pritchett, 1988). Soil surface temperatures and soil moisture levels tended to increase after harvesting because of direct sunlight and reduced transpiration. The higher soil temperatures and soil moisture increased nitrogen mineralization rates, which could cause a release of 7 to 20 times more inorganic nitrogen (nitrate) than in undisturbed forest soils (Binkley, 1984). The released nitrate could be leached from the soil or could be volatilized by denitrification.

Tree species are generally adapted to relatively infertile soils compared to agricultural crops (Jorgensen and Wells, 1986), because forest stands tend to have efficient nutrient cycles (Miller, 1986). However, intensive silvicultural practices may deplete soil nutrients sufficiently to cause forest productivity declines in the second and later rotations (Jorgensen and Wells, 1986; Tiarks and Haywood, 1996).

Issues Regarding Wetland Delineation

The functions and values of wetlands to our environment and society have been emphasized by many environmentalists and scientists, although some confusion still exists about the differences between functions and values. Functions refer to the intrinsic ecosystem processes that are independent of human desires. Values are the extrinsic marketable and non-marketable benefits that are attached to processes or groups of processes and are particularly desirable or valuable to humans (Brinson and Rheinhardt, 1998; Walbridge, 1993). For example, the wetland functions (processes) of photosynthesis, respiration, transpiration, and plant metabolism may result in relatively high rates of net primary productivity, which is valued by humans because of the associated benefits such as timber production, wildlife habitat provision, and recreation. Wetland functions are commonly categorized into five primary groups: hydrology, water quality, habitat and food chain support, nutrient cycling, and socioeconomic (Sather and Smith, 1984).

Hydrology is considered to be the major controlling influence or driving force of the other functions in a wetland system (Gosselink and Turner, 1978). In forested wetlands, hydrology controls soil aeration, soil physical and chemical properties, soil microbial populations, soil nutrient transformations, net primary productivity, plant species presence and abundance, organic matter, carbon storage, and other critical ecosystem processes (Mitsch and Gosselink, 1993). Wetland hydrological processes are dynamic and complex, and the hydrology of forested wetlands is poorly understood. Furthermore, hydrological inputs, outputs, and storage are balanced differently within each forested wetland system such as muck swamps, pocosins, red river bottoms, black river bottoms, minor bottoms, wet flats, and piedmont bottomlands (Mitsch and Gosselink, 1993; Aust et al., 1999).

Although characterization of wetland hydrology is difficult, it is important for jurisdictional wetlands delineation and assessment. The first wetlands delineation manual was produced by the U.S. Army Corps of Engineers (COE) in 1987 (Gaddis and Cubbage, 1998). Hydrological criteria in the manual were “inundation or saturation in vegetation root zone (usually within 30 cm of surface) for more than 12.5% of the growing season; 5-12.5% with supporting evidence.” In the controversial 1989 Federal Manual produced by the Federal Interagency Committee for Wetland Delineation, the hydrologic criteria were “inundation or saturation of soil within 15-46 cm of the surface for seven consecutive days during the growing season in an average rainfall year." In 1991, after the 1989 manual created many regional and technical difficulties, the Bush administration proposed a new wetland hydrology definition (proposed revision), which required that a wetland be “inundated at least 15 consecutive days or saturated to the surface soil for 21 consecutive days during the growing season.” This progression of the hydrology criteria, accompanied by the Bush administration’s ‘No Net Loss’ policy (enforcement of Section 404 Clean Water Act Amendment of 1972) caused confusion and pressure on wetland regulators. This was especially true in the Southeastern Lower Coastal Plain, where wet pine flats' hydrology, soils, and vegetation are often on the boundaries of marginal wetland (delineated as wetland by the 1989 manual but excluded by the 1987 and 1991 manuals) that could cover 77% of the forest (Bengtson et al., 1991). This controversy was further exacerbated by the lack of understanding of wet pine flat hydrology and its effect on the surrounding systems.

Issues Regarding Best Management Practices

Forestry Best Management Practices (BMPs) are guidelines for forest management that were designed primarily to protect water quality but have a secondary benefit of protecting site productivity. These self-regulated forestry practices also benefit forested wetlands management. Many BMPs in the southeastern states suggest minimization of forest soil disturbances or amelioration of disturbed soil by site preparation techniques (Aust, 1994). However, definitions of soil disturbance were not clear, and the original BMPs were not generally based on research results. For example, the Virginia BMP guideline (1989) stated that skidding ruts should not exceed an average of 20 cm deep and 15 m long. Similarly, the South Carolina BMP guideline (1994) stated that the depth and total area of rutting should be minimized to mitigate potential site productivity decrease, but the depth and total area of ruts were not defined. Site preparation techniques including bedding and disking have been utilized to ameliorate disturbed soils (Aust, 1994). However, the spatial and temporal ameliorative effects of site preparation are not well understood.

Objectives

Loblolly pine plantations on wet pine flats are ecologically, socially, and economically important forests. However, the spatial and temporal effects of intensive silvicultural practices and forest operations on long-term forest productivity and surrounding ecosystems are not well understood. Since hydrology is the primary controlling factor of many wetland functions, a detailed investigation of hydrology is critical for understanding wetland processes and their societal implications.

The overall objectives of this study were: (1) to characterize disturbed forest soil morphology and physical properties; (2) to assess their impact on the processes that control site hydrology and site productivity; and (3) to determine the effects of harvesting and site preparation on site hydrology, specifically on the overall hydrological balance and on spatial and temporal patterns of surface water storage.

The following specific questions were addressed pursuant to these objectives:

1. To what extent are soil physical and morphological characteristics changed by forest harvesting and site preparation operations?
2. Do the soil changes persist over time?
3. Do these disturbed soil changes alter site hydrology? Specifically:

a. If forest harvesting negatively affects site hydrology, does subsequent site preparation ameliorate these negative effects?
b. Is the annual water budget in wet pine flats influenced by harvesting and site preparation? If yes, how and to what extent?
c. Are the amounts and spatial patterns of surface water storage influenced by harvesting and site preparation?
d. Do harvesting and site preparation alter the ’wetland status’ of wet pine flats?

CHAPTER II
LITERATURE REVIEW

Wetland Hydrology

Hydrology is the primary determinant of wetland functions. Hydrology is critically important because it controls or modifies several secondary abiotic attributes, including soil reduction-oxidation (redox) potential, soil pH, nutrient fluxes, and dissolved oxygen availability. These abiotic factors control biotic responses and create specific wetland functions and habitats (Gosselink and Turner, 1978).

Wetland hydrological characteristics depend on water sources, velocity of overland flows, renewal rates of surface water, and timing of flooding or ponding (Gosselink and Turner, 1978). Source determines the chemical composition of the surface water, which may influence soil nutrient status. For instance, fast-moving floodwaters provide more essential nutrients, dissolved O_2, suspended minerals, and organic matter than do slow-moving floodwaters. Nutrient input by precipitation is less than by floodwaters. Higher water velocity favors turbulent flow that can erode bottom sediments, transfer suspended materials, and deposit coarse suspended materials as sediments. Localized relief (micro-relief) is created by this dynamic fluvial process, and micro-relief provides a variety of soil moisture and nutrient conditions that will favor certain species of plants.

Surface water renewal rate can be determined from the water depth, velocity, and frequency and duration of flooding. Timing of flooding and its duration affect the succession and maturity of wetland plant communities. The effects of these factors are integrated in the wetland water balance.

Wetland Water Balance

Wetland water balances are complex because they consist of many different water inputs, outputs, and storage, and each wetland system water balance is somewhat unique (Mitsch and Gosselink, 1993). The water balance for an open system is conceptualized by a mass balance equation for a specified wetland volume over a specified time period (Table II-1). Water inputs for a unit area of the surface soil of a typical southeastern wet pine flat include precipitation (PPT), groundwater inflow from below the confining horizons, and lateral surface inflows, which include overland and perched water flows. The outputs include evapotranspiration (Et) (which includes evaporation and transpiration), and interception, lateral surface outflows, and groundwater outflow.

Table II-1. Components of a conceptual water mass balance equation for a surface soil of a typical southeastern wet-flat pine plantation.

Inflow	-	Outflow	=	Storage
· Precipitation		· Evapotranspiration (evaporation, transpiration, interception)		
· Lateral surface water inflow (surface and perched water)		· Lateral surface water outflow (surface and perched water)		· Change in water stored per unit area over a given time period
· Groundwater inflow		· Groundwater outflow (leakage)		

Determination of each water balance component in the wet pine flats is difficult due to several reasons. First, rainfall is extremely variable by location and year. For example, summer thunderstorms produce localized intense rains in the region. This type of rain sometimes exceeds 50 mm per hour at one location, while nearby locations less than 1 km distant have no rain. Annual precipitation in Walterboro, South Carolina, for example, varies from 1055 to 1581 mm with 20% probability (USDA Soil Conservation Service, 1982). Secondly, because uneven patterns of precipitation produce uneven surface and subsurface water distribution, evapotranspiration and soil water storage are also variable. Third, determination of surface and subsurface water flow is difficult due to the flat topographical features and man-made structures such as drainage ditches and road systems. These structures significantly alter site surface hydrology (Skaggs et al., 1980).

The water budgets for two forested wetlands in the Southeastern Lower Coastal Plain were determined at Okefenokee Swamp, Georgia (Rykiel, 1984), and a pocosin swamp in North Carolina (Richardson, 1983) (Table II-2). These studies showed that the wetland water budget for non-alluvial wetlands was characterized by large amounts of precipitation (1170 to 1310 mm yr^{-1}) as the main input source and evapotranspiration (670 to 880 mm yr^{-1}) as the main output source, slow and low amounts of lateral in- and outflow, very small annual storage fluctuation ($\Delta V/\Delta t \cong 0$), and very small groundwater in- and outflow (Mitsch and Gosselink, 1993).

Several studies in Florida cypress pond/wet pine flats and North Carolina pine flats revealed complex and dynamic wetland hydrology (Table II-2). The Florida studies showed an annual precipitation range of 1070 to 1420 mm and an evapotranspiration range of 770 to 1310 mm; the highest precipitation of 1840 mm was reported by Riekerk (1985). The North Carolina studies also showed wide ranges of annual precipitation and evapotranspiration (1109 to 1870 mm and 782 to 1041 mm, respectively) (Amatya et al., 1996).

Table II-2. Summary of forested wetland water budgets in the Southeastern Lower Coastal Plain of the United States.

Location	PPT	Et	Surface Water Drainage	Net Groundwater	Reference
	----------------------	(mm yr^{-1})	----------------------		
Okefenokee Swamp Upland, GA	1310	-880†	-390	-40	Rykiel (1984) ‡
Pocosin, NC	1170	-670	-490	-10	Richardson (1983) ‡
Cypress Pond/Pine Flat, FL	1070	-1270	510	n/a	Heimburg (1976) §
Pine Flat, FL	1420	-770 to -1180	n/a	n/a	Heimburg (1984) ¶
Cypress Pond/Pine Flat, FL	1280	-1310	n/a	n/a	Riekerk (1989) §
Cypress Pond/Pine Flat, FL	1140	-1150	n/a	n/a	Riekerk et al. (1995) §
Wet Pine Flat, NC	1243 #	-1056	-218	n/a	McCarthy et al. (1991)
Wet Pine Flat, NC	1499††	-943	-387	n/a	Amatya et al. (1996)

† Negative sign indicates output source.
‡ As cited in Mitsch and Gosselink (1993).
§ As cited in Fares et al. (1996).
¶ As cited in Ewel and Smith (1992).
# Values are mean of three sites.
†† Values are mean of three sites between 1988 and 1992.

Accurate actual evapotranspiration from soil and plants can be determined by the lysimeter method (Hewlett, 1969), but this method involves large and costly apparatus and time-consuming maintenance (Brooks et al., 1997). Numerous methods have been developed to estimate evapotranspiration. The evaporation pan method is one of the direct estimation techniques, which measures actual evaporated water volume from a free water surface, and the measurement is converted to potential or actual evapotranspiration by use of pan coefficients. The other direct estimation method was developed by White (1932) and was based on the observed diurnal fluctuations of the water table. This method requires a continuous water table measurement and assumes relatively constant rates of recharge. The Thornthwaite (Thornthwaite and Mather, 1955), Penman (1948), Penman-Monteith (Monteith, 1965), and Hammer and Kadlec (1983) equations are used to indirectly estimate potential evapotranspiration (PET) (Mitsch and Gosselink, 1993; Brooks et al., 1997). Thornthwaite's equation uses only mean monthly temperature as a variable. Kadlec et al. (1988) reported that this method tends to underestimate PET, especially in an arid environment. The Hammer and Kadlec equation uses a linear regression approach which includes incident solar radiation, air temperature, relative humidity, and wind speed as variables. The estimated PET is relatively close to actual ET (Hammer and Kadlec, 1983), but because of the linear structure of the equation, the regression coefficients may be specific to a wetland type. The Penman and Penman-Monteith equations are more process-oriented models, and they require many weather variables and relatively complex calculations. However, many studies have reported that the results obtained with these equations were the most accurate and flexible among the estimation methods (McCarthy et al., 1991; Persson and Lindroth, 1994; Abtew, 1996; Amatya et al., 1996; Souch et al., 1996; Schiller and Cohen, 1998).

The determination of groundwater fluxes requires knowledge of the regional groundwater hydrology. Studies of these interactions in an interior northern wetland indicated very active groundwater-surface water interactions (Roulet, 1990), significant groundwater influence on watershed discharge (Verry and Boelter, 1978; Waddington et al., 1993; Devito et al., 1996), and water chemistry (Hill, 1990; Devito and Dillon, 1993). In the Southeastern Lower Coastal Plain flatwoods wetlands, the groundwater-surface water interaction was reported to be very small (less than 12 mm yr^{-1}) (Heath, 1975) or negligible (Skaggs et al.1991). Studies of a South Carolina wet pine flat showed relatively high groundwater levels during winter (higher than 50 cm below the surface), indicating potential groundwater-surface water interaction in these wetlands (Preston unpublished data). However, precise determination of these interactions in wet pine flats is very difficult because of spatial variations in geology and topography.

Effects of Wetland Hydrology on Biogeochemistry

Wetland biogeochemical cycles are closely tied to the hydrologic cycle (Mitsch and Gosselink, 1993). Since precipitation is the major water input source in the wet pine flat system, nutrient inputs to the system are relatively small. Seasonal flooding and backwater flooding, which are major sources of nutrient inputs to several of the other wetland systems, are extremely rare in wet pine flats.

The nutrient retention capacities of sandy soils, which are typical of the surface soil in wet pine flats, are also small. Because of the low nutrient input, low nutrient retention capacity, and relatively high precipitation of the region, which accelerates nutrient leaching, the wet pine flat system tends to be a nutrient-impoverished system. Ponding (inundation) creates anaerobic conditions within a wetland soil, followed by a chain of reduction processes involving O_2, NO_3^-/NH_4^+, Mn^{4+}, Fe^{3+}, SO_4^{2-}, Mn^{2+}, CO_2, and organic matter, caused by anaerobic and facultative microbial activities (Mitsch and Gosselink, 1993).

Effects of Forest Operations on Wetland Hydrology and Soils

Common silvicultural practices may have significant effects on wet pine flat hydrology. Drainage ditches significantly increase peak discharge and decrease base flow (Skaggs et al., 1991). Thinnings of pine plantations have a large effect on interception rate; therefore, thinning decreases total evapotranspiration (Leyton et al., 1967). However, evapotranspiration changes due to forest harvesting are still not well known. Aust et al. (1993, 1995, 1998a) found that severe soil disturbance, caused by wet-weather harvesting in a wet pine flat of South Carolina, increased perched water tables and altered hydrology at the study site. They concluded that wet-weather harvesting altered soil physical properties, which caused the water table and site hydrology alterations.

Each component of the mass balance equation can be altered by forest operations (Figure II-1). For example, a harvesting operation severs the transpiring stems and removes the canopy, thereby reducing tree transpiration and interception. Harvesting operations may also reduce surface and perched water flow by interrupting the lateral flow of perched water via compaction, rutting, and churning (Figure II-1B). Although the same harvesting operation can increase soil water evaporation and herbaceous transpiration and interception, such operations often increase water tables. Bedding, a common site preparation technique used in the lower coastal plain region, increases soil water evaporation by exposing bare soil and controlling herbaceous vegetation (Figure II-1C). Mole plowing redistributes ponded water to elevated areas within a plot, which increases soil water availability at the elevated dryer areas while decreasing ponded water level. However, these harvesting and site preparation effects on wet pine flat water budgets have not been characterized.

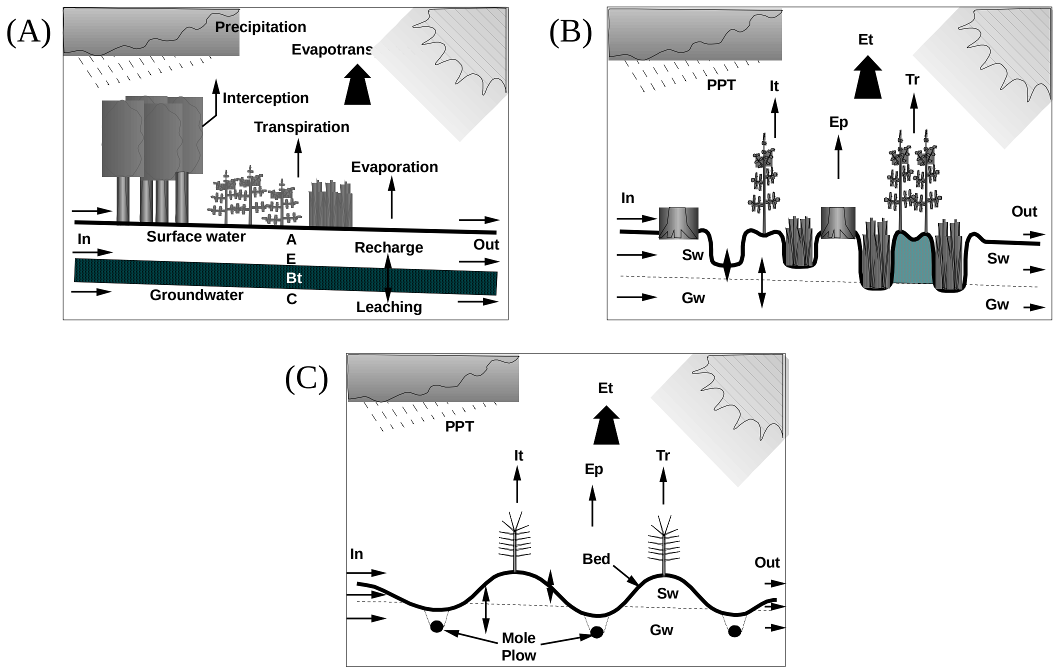

Figure II-1. Schematics of the water balance for wet pine flats under typical (A) undisturbed, (B) post-harvesting, and (C) post-site preparation conditions.

Forest Harvesting and Site Preparation Effects on Wetland Soils

Soils of the Southeastern Lower Coastal Plain wet pine flats are often saturated during the growing season due to frequent intense rain events and poor drainage caused by flat topography and impermeable subsurface soil layers. These moist-wet soils are susceptible to severe disturbance by heavy machinery (Burger, 1994). Effects include soil compaction and puddling, and changes in soil physical properties and soil biota.

Mechanisms of Soil Compaction and Puddling

Several studies have examined the processes and characteristics associated with compacted agricultural and forest soils (Hillel, 1982; Pritchett and Fisher, 1987; Marshall et al., 1996). Heavy equipment operating on moist soils often causes soil compaction and soil surface smearing (Davies et al., 1973). Tractor tires apply compressive forces to the soil's surface. This compressive force is a combination of the normal downward force associated with equipment mass and gravity and the shear forces that are brought about by vehicular speed, vibrations, and tire characteristics. Soil compaction occurs when the compressive force results in relative movement among the soil particles, leading to the collapse of larger pores and a decrease in porosity. The ability of a soil to resist compressive forces is a function of several variables, including soil texture, soil organic matter, and soil water content. Soil water content is the most widely fluctuating variable, and its frequent variations cause soil compaction and rutting to be common phenomena (Greacen and Sand, 1980; Hillel, 1982).

At low water contents, soil water commonly exists as a thin water film around the soil particles and the connecting structures, such as clay bridges. As soil moisture content increases, the thickness of the water film increases. This water film weakens the connecting structures and decreases frictional forces between the soil particles. Therefore, moist soils are more susceptible to compaction, especially when soil water content is between the plastic and liquid limits (Greacen and Sand, 1980; Hillel, 1982).

Wheel slip also causes smearing on the soil surface and causes additional soil compaction (Davies et al., 1973). Wheel slipping induces shear forces on a moist soil, reorients soil particles, and forms horizontal platy structures (pressure faces), a process commonly referred to as puddling. Soil disturbances produced by the combination of static stresses and dynamic shear forces on moist soils generally achieve higher levels of compaction than are caused by the static stresses alone on dryer soils (Bodman and Rubin, 1948). Davies et al. (1973) reported that increased wheel slippage resulted in higher shear strengths, soil compaction, and higher bulk density values. The higher bulk density values were also associated with lower porosity and water permeability and higher soil mechanical resistance and moisture content.

Under total soil saturation, soil compaction is not possible, although soil churning usually increases. At soil water contents above the liquid limit, the water-filled soil pores are not compressible (Aust and Lea, 1992). Under this condition, traffic-induced shearing stresses reorganize the soil particles. The reorganization usually causes clay-polyplate slippage, destroys soil particle bonds (aggregate structures), and abrades colloidal coating materials from sand grains (Koenigs, 1963). Multi-directional force produced by large equipment tires moves large soil particles and flocculates fine soil particles in excess soil water. Soil rutting, churning, and 'plastic mud' are the results of heavy machines operating on these hydrated soils.

Soil Properties Affected by Soil Compaction and Puddling

Severe soil disturbances cause significant alteration of soil physical and hydraulic properties (Naphade and Ghildyal, 1971; Marshall et al., 1996). Jamison (1963) conducted a laboratory experiment that examined the air-water relations within packed and puddled clay-textured soils and found that heavy packing and puddling decreased macroporosity significantly, but available water capacity was increased by puddling. Apparently, the packing process, which is similar to compaction, decreased macropores but had little effect on available water capacity and micropores. The puddling process reorganized most of the macropores as smaller micropores. The puddled soil also had low permeability due to the decreased volume of macropores, lower resistance to external forces, and homogeneous structure because of soil structure destruction (Koenigs, 1963). Gradwell (1966) measured hydraulic properties of medium-textured, alluvial soils in pastures and found that puddled soils had reduced water holding capacity, lower water retention, and a narrower range of water retention than unpuddled soils. Huang et al. (1996) showed that soil disturbance due to harvesting operations significantly decreased surface soil sorptivity and unsaturated hydraulic conductivity. These laboratory experiments and field studies indicated that puddled soils contained less plant-available water, and that water infiltration rates within the puddled soils were lower than in undisturbed soils, leading to less desirable soil conditions for seedling growth.

Soil disturbances produced by the heavy equipment used for forest operations are deeper and more severe than pasture and agronomic soil disturbances. The depth of the disturbances suggests that heavier equipment may have a more significant effect on soil physical and hydrological properties and future forest productivity. Many studies have shown that rubber-tired skidders severely disturb forest soil physical properties such as bulk density, macro-, micro-, and total porosity, and saturated hydraulic conductivity (Dickerson, 1976; Gent et al., 1983, 1984).

Burger et al. (1989) examined the effects of rubber-tired skidding with a variety of tire sizes and number of passes on a somewhat poorly drained clayey soil in the Southeastern Lower Coastal Plain. They found substantial disturbance in soil horizons below disturbed surface soils in skidding tracks. Aust et al. (1993) observed higher water tables and an alteration of site hydrology following wet-weather harvesting in South Carolina. The hydrology alteration was caused by increased bulk density and decreased macroporosity and saturated hydraulic conductivity associated with primary skid trails. Aust et al. (1995) also compared dry- and wet-weather harvesting effects on soil physical properties in a wet pine flat and concluded that dry-weather harvesting created soil compaction and subsequent soil physical property changes in primary and secondary skidding trails, and wet-weather harvesting created more severe soil disturbance and complex soil physical property changes. Miwa et al. (1998) described severely disturbed subsurface soil layers in two-year-old, deeply rutted soils in a wet pine flat of South Carolina. The disturbed layers showed a dark gray to olive soil matrix color with prominent mottles caused by slow drainage and a subsequent, prolonged soil saturation period. Massive or platy structure, low hydraulic conductivity and porosity, and high bulk density and soil stability index (the ratio between air and water permeability) occurred due to heavy machine operations. These characteristics indicated that a significant alteration of soil hydrologic properties and site hydrology had occurred due to wet-weather harvesting.

Soil Disturbance Effects on Soil Biota

Soil compaction affects root growth, soil macro fauna, microbial activities, and biological interactions (Whalley et al., 1995). Root cells elongate when the turgor pressure of the cell is greater than the surrounding soil pressure (Whalley et al., 1995). Several studies, however, reported that root elongation was reduced more than 50% by 40 kPa of soil pressure, which was significantly lower than an earlier finding of maximum root growth pressure of 1,300 kPa (Whalley et al., 1995). Other studies showed that several agricultural plants reduced their root mass when surface soil was compacted, and Whalley et al. (1995) concluded that lower crop yields and higher plant mortality might be caused by soil compaction because of low nutrient uptake from the surface soil and a longer soil wetting period.

Although tree root systems are generally more tolerant of soil compaction and wet conditions than agronomic crops, long-term forest productivity decreases and gradual plant community alterations might be the direct and indirect effects of soil compaction. Root hair damage by soil disturbance is detrimental for tree growth, since surface layers of forest soil are the main nutrient reservoirs. Therefore, disturbances of forest soil may affect plant successional processes, including regeneration, plant growth, and reproduction; consequently, the plant community might be altered in the long term.

Surface soil compaction reduces soil macrofauna activity and populations, especially anecic and endogeic earthworms[3], by reducing oxygen supply (Whalley et al., 1995). Soil strength did not affect earthworm activity. Studies showed that earthworm tunnel length did not change at soil pressures between 0 and 3000 kPa with a given soil moisture, but earthworm activity increased as soil water potential decreased below -10 kPa. Earthworms have important roles in nutrient recycling by breaking down large organic matter debris, developing stable nutrient reserves by mixing organic and inorganic soil materials, improving soil structure by increasing aggregation, and providing continuous macropores for roots by creating biopores (Whalley et al., 1995). Therefore, disturbance of earthworm activity may reduce forest productivity.

Soil microbial activity is affected by oxygen infiltration rate, soil moisture regime, soil temperature, inorganic nutrient level, and amount and nature of organic matter (Pritchett and Fisher, 1987). Soil compaction changes soil microbial activities by decreasing the oxygen diffusion rate and by increasing the soil wetting period (Whalley et al., 1995).

Bedding as an Ameliorative Practice for Soil Disturbances from Harvesting

Over the past decade, bedding has been suggested as a potential ameliorative practice for wet-weather harvest disturbances (Aust, 1994). It is being used on relatively

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[3] Anecic earthworms are deep-burrowing surface feeders, and endogeic earthworms are soil humus feeders (Whalley et al.1995)

wet sites in the southeastern coastal plain to ameliorate soil compaction or puddling. It is commonly used to elevate seedlings above the saturated soil layer to improve their survival, and to control vegetative competition, thus enhancing seedling growth (Mann and Derr, 1964).

Since the 1970's, several studies have been conducted to evaluate the effects of bedding on southeastern pine flatwoods. However, the results of each study were often site-specific, and the actual effect of the bedding on long-term forest productivity is still not conclusive. Bedding studies in southeastern Georgia (Worst, 1964; May et al., 1973; Saigumba and Anderson, 1979) found that seedling survival was improved by bedding and harrowing in the relatively wet, sandy soils. Tree height and diameter in the bedded and harrowed sites were significantly higher than in control and scalped sites at age 4, 10, and 17. Similar results were reported on typical wet pine flats in the eastern Carolinas and Virginia. Seedling survival and growth in bedded plots were higher than in herbicide-treated and disked plots, and tree height, basal area, and stand volume were significantly higher in the bedded plots (Terry and Hughes, 1975; Hatchell, 1981; Gent et al., 1986; McKee and Hatchell, 1986; Andrews, 1993; Scheerer et al., 1994; Aust et al., 1998a). Scheerer et al. (1994) found that bedding partially ameliorated the soil physical properties of severely disturbed soils on wet pine flats in South Carolina.

Many bedding studies have been conducted on poorly drained sandy soils in Florida flatwoods (Langdon, 1962; Bethune, 1963; Haines and Pritchett, 1964; McMinn, 1969; Lennartz and McMinn, 1973; Mann and McGilvray, 1974; Schultz, 1976; Pritchett, 1979; and Burger and Pritchett, 1988). They found that bedding significantly improved seedling survival and growth on wet sites, especially the higher beds which provided thicker aerated root zones (Mann and McGilvray, 1974). They also found that the bedding effect was no different from other mechanical site preparation effects when bedding was used on dry and intermediate sites.

Haines and Pritchett (1964) reported that complete clearing (scalping and harrowing) showed better growth than bedding for some sites, and Lennartz and McMinn (1973) speculated that clearing provided a harrowing effect that controlled competing vegetation more than bedding. Therefore, clearing was more beneficial to established seedlings, whereas bedding provided more suitable soil environments for early seedling survival and growth. The benefit of clearing on seedling growth was explained by the higher root mass, lower number of deformed roots, and better lateral root distributions (Haines and Pritchett, 1964). These results contradicted the findings of Andrews (1993) for sites in the lower coastal plain of Virginia, which showed that scalping on bedded plots decreased organic matter and lowered soil nutrient status.

Burger and Pritchett (1988) examined site preparation effects on soil chemical properties and seedling growth. They found that intensive site preparation (burned-bladed-harrowed-bedded) increased nitrogen, phosphorous, and potassium in the soil solution, although it decreased total nitrogen in the soil because burning and blading reduced surface soil organic matter, and harrowing and bedding caused a higher mineralization rate due to the increased soil temperature and soil moisture levels. High nutrient availability in the bedded area caused greater seedling growth.

Two rotations of bedded slash and loblolly pine were studied in central and southwest Louisiana (McKee and Shoulders, 1970; Derr and Mann, 1970, 1977; Mann and Derr, 1970; Cain, 1978; Haywood, 1980, 1983, 1994; Tiarks, 1983; Tiarks and Haywood, 1996). The sites were characterized by moderately well-drained to poorly-drained silt loam, low-fertility soils, and relatively dry conditions during the growing season. Control, flat disking, bedding, and harrowing site preparations were installed in the first rotation, and only burning on the original treatments was used in the second rotation. They concluded that poorly formed and settled beds decreased seedling survival of the first rotation, but early height and diameter growth of the first rotation was improved by bedding. This high growth rate in the bedded sites continued until age 10-13, but the growth rates of all treatments became equal after 13 growing seasons. In the second rotation, seedling height was actually lower in the bedded areas. Tiarks and Haywood (1996) speculated that the negative bedding effect in the second rotation might be caused by nutrient depletion during the first rotation; however, the soil chemical characterization did not support their speculation. The soils in the study site had nutrients near critical levels; therefore, a small decrease in the nutrients could have affected tree growth, even if the decrease was not statistically and practically significant.

Many studies showed that bedding increased seedling survival and initial growth, especially on relatively wet sites. Shiver and Fortson's extensive survey results (1979) also supported this general conclusion. They surveyed tree height and diameter at breast height of 10-year-old slash and loblolly pine plantations on 498 plots in the lower coastal plain of South Carolina, Georgia, and Florida, and concluded that the yield of mechanically site-prepared stands was higher than the yield of non-site-prepared stands as long as survival of the stand was acceptable. Shiver et al. (1990) studied the specific effects of site preparation methods on slash pine growth in spodosols and non-spodosols of the lower coastal plain of Georgia and northern Florida and found that tree heights and diameters at age eight years were significantly higher in bedded and herbaceous control plots, but decreased on burned spodosol plots because of low nutrient pools in the soils. However, early advanced growth was diminished between age 10 and 17 years (Haywood, 1983; Tiarks, 1983; Allen and Campbell, 1988), and annual growth of non-bedded sites exceeded that of bedded sites by age 35 years (Wilhite and Jones, 1981).

Some studies indicate that bedding may have detrimental or beneficial effects on soil properties. Site preparation, including bedding and plowing, in wet soils tends to compact and smear the soil below the furrow (Swain, 1975). This compaction and smearing decreases soil water permeability and causes an anoxic environment. Gent et al. (1983) evaluated bedding amelioration effects on physical properties of original surface soils and observed an increased bulk density and decreased hydraulic conductivity and porosity in the original surface soils of the skid trails and harvested plots. They concluded that bedding did not ameliorate the original surface soil, although the actual bed did have improved soil properties. Schultz (1976), Pritchett (1979), and Attiwill et al. (1985) reported that bedding improved available soil nutrients by concentrating organic matter-rich surface soils. Also, Schultz (1976) reported that bedding changed microclimate significantly. This might increase organic matter decomposition and mineralization rates (Burger and Pritchett, 1988), which could increase available soil nutrients for short periods.

Natural Recovery of Disturbed Soils

Estimates of natural recovery of soil properties following soil disturbances have been reported. Perry (1964) compared the infiltration rate of 26-year-old ruts and undisturbed areas in North Carolina Piedmont soils and estimated that 40 years would be needed for natural recovery to the original infiltration rate. Hatchell et al. (1970) had measured bulk density in logging decks and evaluated the recovery rate during 19 years after the disturbance. They estimated that the bulk density recovery period would be about 18 years in the Atlantic Coastal Plain. Dickerson (1976) measured physical properties of disturbed loam and silty clay loam soils in the coastal plain of northern Mississippi. Bulk density values in rutted and logging-disturbed areas were 11% and 4% higher, respectively, than that in an undisturbed area after five years. They estimated that natural recovery to the original bulk density values would require 12 and 8 years, respectively.

In the review by Webb et al. (1983), the soil restructuring process could be expressed as an exponential-decay curve. However, because the soil restructuring process is very complex and gradual, detailed information of the process is still unknown. Generally, the most important natural factors to the initial soil structural recovery process are 2:1-expanding clay (shrink-swell clay) contents, soil fauna and flora populations, and freezing-thawing cycles (Koenigs, 1963; Larson and Allmaras, 1971; Greacen and Sands, 1980; Webb et al., 1983). Shrink-swell clay content and soil fauna and flora population are important in the Southeastern Coastal Plain because of its alluvial soil parent material with mixed mineralogy and warm temperate climate.

Soil Structuring Due to Expanding Clay

A common clay mineral responsible for soil shrinking and swelling is montmorillonite (Koenigs, 1963). The expanding mechanism is explained by the cations, such as sodium (Na^{+}), potassium (K^{+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}), held on the internal surface of montmorillonite (Bohn et al., 1985). These cations expand by hydration when water molecules are available. The cations on the external surface form a Diffuse Double Layer (DDL), and because of the higher cation concentration in the DDL, water molecules are drawn into the DDL by osmotic forces, causing the expansion of the DDL and the repulsion of adjacent expansive clay particles.

Soil shrinkage occurs when aggregates lose the intra-aggregate water that causes reorganization of the soil particles and decreases the porespace of the aggregate (Larson and Allmaras, 1971; Brown, 1977). This is often observed during normal shrinkage, which is the shrinking stage when the volume of water lost is equivalent to the decrease in aggregate volume (Reeve and Hall, 1978; Newman and Thomasson, 1979).

Soil shrink-swell potential is affected by the structural arrangement among soil particles (Koenigs, 1963), shrink-swell clay content, soil water content, and cation concentration of the water (Bohn et al., 1985). Forces acting on the soil structure are swelling forces, which include hydration of cation and osmotic expansion, and counteracting frictional forces, which include Madelung force (clay-polyplate attractive force) and edge-plate/organic matter-plate binding forces (Koenig, 1963). Since part of the swelling process depends on osmotic dilution of the DDL, higher soil water content (available water for diffusion) and cation concentration of soil solution affect water diffusion into clay-polyplates (Bohn et al., 1985). When the cation concentration of soil water is significantly lower than the concentration of the DDL, the osmotic potential between the clay particle surface and soil water is high; therefore, more water is drawn into the DDL, and the clay particles are dispersed (i.e., soil swelling). Soil water content is the other important factor that determines soil swelling. The more bulk water in the soil macropores, the greater the soil swelling.

Soil shrinking behavior and the relationships among soil shrinking-swelling, soil physical property change, and the effects on plant growth have been studied by many researchers. Generally, a relatively small amount of expandable clay, even 10 to 15% of expandable clay in the total soil weight, causes significant cracks in a soil (personal communication, P. J. Thomas, 1998).

McGowan et al. (1983), Pillai-McGarry and Collis-George (1990a), and Sarmah et al. (1996) found that disturbed soil structure was improved by repeated wet-dry cycles. Pillai-McGarry and Collis-George (1990a) compared expanding and non-expanding clayey soils under different mechanical treatments (ponded and puddled) and wetting cycles (one through seven cycles). They found that multiple wet-dry cycles produced polygonal cracking patterns and small crumbed aggregates because repeated shrinking-swelling broke weaker soil particle bonds and contracted strongly bound soil particles as finer and stable aggregates. In the mechanical treatment comparison, they found that the puddled treatment produced larger and more angular-shaped aggregates than the ponded treatment alone. Puddling broke soil aggregates and homogenized soil structure; therefore, the strength of soil particle bonds became relatively uniform, and shrinking-swelling was less effective in producing smaller and more stable aggregates. They also found that extended drying periods did not have a significant effect on soil cracking.

McGowan et al. (1983) observed that soil cracks occur with slight soil dryness. Once soil cracks are open, the cracks do not close completely unless the soil is saturated for a long period because of the relatively low saturated hydraulic conductivity of the clayey soil and generally slower rehydration process due to hysteresis. Sarmah et al. (1996) found that flood wetting of soil restructured disturbed soils more efficiently than rain wetting. This difference was probably caused by hydraulic potential difference between the two methods and surface crusting effect caused by the rain wetting method. Flood wetting tends to create higher hydraulic potential on the soil surface because the water ponded above the soil surface increases infiltration rate. Rain wetting tends to produce crusting on the soil surface because the force of falling water disperses and compacts the surface soil particles. Therefore, the rain wetting probably decreased infiltration rate. These results indicated that frequent wet-dry cycles with flood wetting (waterlogging) could restructure disturbed clayey soils.

Soil physical property alterations, which are produced by shrink-swell soils, are generally beneficial for plant growth (Blackwell et al., 1985). Typical soil property changes include increased aggregate stability (McGowan et al., 1983; Pillai-McGarry and Collis-George, 1990a, 1990b), macroporosity, infiltration, and saturated hydraulic conductivity (Brown, 1977; Bullock et al., 1985; Blackwell et al., 1985; Sarmah et al., 1996), decreased bulk density, water table, and soil strength (McGowan et al., 1983; Blackwell et al., 1985; Sarmah et al., 1996), and increased soil aeration and redox potential (Blackwell et al., 1985). Larson and Allmaras (1971) and Goss et al. (1978) showed that soil cracking regenerated continuous soil macropore columns, and the macropores enhanced water infiltration, soil gas exchange, and plant root extension. Furthermore, Mazurak (1950) found that clays with a larger surface area, such as montmorillonite, produced more stable aggregates than those with lower surface areas. These results indicated that the Southeastern Coastal Plain soils, which commonly consist of appreciable amounts of montmorillonitic clay (Bohn et al., 1985), have high self-repairing potential, and this may enhance plant root growth.

Soil Forming Due to Soil Biological Activities

Soil biological activities are another essential soil restructuring process (Webb et al., 1983). However, detailed soil biological activities and their effects are not well understood because soil organisms are very diverse, and their interactions are complex and dynamic (Gosz, 1984; Waring and Schlesinger, 1985; Buol et al., 1989). Furthermore, few studies have detailed forest soil biological activity in terms of disturbed soil restructuring. However, the basic functions and mechanisms of the principal soil organisms, and silvicultural effects on their biological activities, are generally known.

Among the diverse soil organisms, earthworms, bacteria, and fungi are especially important for the initial breakdown of coarse organic debris (logging slash) and litter (Gosz, 1984; Waring and Schlesinger, 1985; Pritchett and Fisher, 1987). The primary effects of the initial fragmentation of large organic debris are the physical and chemical breakdown of the stable cellular structure and an increase in the surface area of the organic matter for further microbial decomposition (Waring and Schlesinger, 1985).

Earthworms are probably the most important soil macrofauna in the temperate forests because they (1) are abundant in the forest system, (2) fragment and mix litter and partially decomposed organic materials with mineral soil, (3) create continuous macropore space that improves water permeability and soil gas exchange, and (4) enhance soil structure (Gosz, 1984; Waring and Schlesinger, 1985; Pritchett and Fisher, 1987). Unlike plant roots that compress the surrounding soil, earthworms do not compact soil because they ingest soil materials and organic matter, and this process creates new void space (Dexter, 1978). Some surface-voiding earthworms improve the structure of highly compacted soils even where the soil strength is 3.0 MPa. McLean and Parkenson (1997) studied epigeic earthworms (*Dendrobaena octaedra* Savigny) in intact, undisturbed litter-soil cores for six months and observed O horizon decreases due to mixing of the fragmented litter and humus layers (Oe and Oa layers, respectively) with the mineral soils. They also found that high levels of earthworm activity decreased fungal activity because of mycelium disruption and increased efficiency of bacterial carbon utilization because the earthworms predigested stable carbon.

Although many different types of bacteria are active under diverse environments, bacterial activity is generally affected by soil moisture, temperature, litter quantity, and litter decomposition stage (Lundgren, 1982; Berg et al., 1998). Lundgren (1982) found that bacterial activity was increased by clearcutting and slash remaining in a Swedish boreal Scots pine (*P. sylvestris* L.) forest. The author concluded that the remaining slash reduced evaporative soil moisture loss, and the higher soil moisture increased bacterial activity. Berg et al. (1998) found that bacterial activity in the humus layer was higher than that of upper less-decomposed organic layers and beneath soil mineral layers. This was because humus is composed of partially decomposed, highly fragmented organic material, and the temperature and moisture of the humus layer was more stable than those of upper organic matter layers.

Although fungal activity and abundance are also functions of soil moisture, temperature, and organic matter quality and quantity, fungal activity is less susceptible to soil moisture and temperature (Baath and Soderstom, 1982; Berg et al., 1998). Berg et al. (1998) characterized fungal activity and distribution in a Netherlands Scots pine forest and found higher fungal activity in an upper organic layer (Oi layer). This activity decreased as organic matter decomposed (Oe and Oa layers). They also found that a higher carbon/ nitrogen ratio caused higher fungal activity. These results agreed with a previous nitrogen fertilization and microbial activity study (Verhoef and Brussaard, 1990), which concluded that nitrogen fertilizer application on acidic coniferous forest soils shifted fungus-dominated microbial systems to bacteria-dominated microbial systems because of a lowered carbon/nitrogen ratio. These results indicated that fungal activity is more affected by litter nutrient content and the decomposition stage.

Soil acidity has a large influence on soil biological activities (Pritchett and Fisher, 1987). Acidic forest floors, such as some pine forest floors, inhibit earthworm and bacteria activities (Waring and Schlesinger, 1985) because the optimum soil pH for earthworm activity is between 6.0 and 8.0. Also, many aerobic cellulose-decomposing bacteria are only active where soil pH is higher than 5.5. Although some earthworm species can be active under acidic soil conditions (McLean and Parkinson, 1997), the primary decomposing agents in the acidic forest floor are fungi and mesofauna such as Protozoa, Nematoda, and Enchytraeid (Gosz, 1984; Waring and Schlesinger, 1985), and Isopoda (Soma and Saito, 1979).

Effect of Silvicultural Practices on Soil Natural Recovery Processes

Forest operations may have significant effects on soil recovery processes. The principal natural soil physical mechanism for restructuring of disturbed soils in the Southeastern Lower Coastal Plain is soil shrinking and swelling by expanding clays. Shrinkage and swelling are triggered by soil water abundance, soil water chemistry, water source, and wet-dry frequencies. Forest harvesting operations in wet sites typically increase the soil water content because harvesting reduces evapotranspiration and decreases soil internal drainage. As a result, there is abundant water to swell expandable clay particles. However, because of prolonged soil saturation periods, soil wet-dry frequency would be decreased, implying that the soil particle restructuring process due to soil shrinkage could not be achieved.

Typical site preparation techniques, such as bedding, are intended to ameliorate surface-compacted soils by loosening the soils and elevating them above the water table. These elevated soils are exposed to further abiotic and biotic weathering processes. (i.e., the soil restructuring process is accelerated.) However, disturbed subsurface soils that may have a significant effect on site hydrology are not ameliorated by common site preparation techniques because most of the techniques do not aerate and loosen the subsurface soils. Therefore, they probably do not improve the internal soil drainage and water table fluctuations (Blake et al. 1976; and Bullock et al., 1985).

Forest operations also have significant effects on the forest soil biological activities because the operations alter the forest soil environment. In the Southeastern Lower Coastal Plain wet pine forests, typical forest harvesting operations leave large amounts of organic debris and often mix the organic matter into the surface soils. Biologically important soil climatic changes produced by harvesting include higher surface soil temperatures and perched water tables. These changes probably increase fungal activity in the surface organic debris because of accumulated fresh biomass. The changes also probably decrease earthworm and aerobic bacterial activities in the surface soil, and increase anaerobic bacterial activities.

Typical site preparation in the region includes drum chopping and bedding, which break down large organic debris, incorporate organic matter in surface soil, and loosen compacted, rutted, and churned soils (Harms et al., 1998). These processes produce more aerated soil volume, improved soil hydraulic properties, and higher organic matter content in the elevated bedded soils. These amendments are likely to increase fungal, bacterial, and earthworm activities. However, disturbed subsurface soils may not be ameliorated to the same extent as surface soils because the subsurface soils typically have heavier soil textures (i.e., high soil strength), contain less organic matter (i.e., carbon and nitrogen source), and are saturated for longer periods (i.e., limited biological activities).

In short, the most important forestry practices to enhance natural soil recovery processes in disturbed wet sites are soil water management and site preparation techniques. These ameliorative treatments can provide adequate soil moisture for soil organisms and create frequent wet-dry cycles for the shrink-swell process. Treatments such as bedding combined with a subsoiling technique such as mole plowing (Spoor et al., 1982) may satisfy both requirements.

CHAPTER III
MATERIALS AND METHODS

Site Location and Physical Description

Location

The project site is located in Colleton County, South Carolina, latitude 32°55’, longitude 80° 30’, approximately 30 miles west of Charleston, South Carolina (Figure III-1). The study was established in intensively managed loblolly pine plantations in the Lower Coastal Plain owned by Westvaco Corporation.

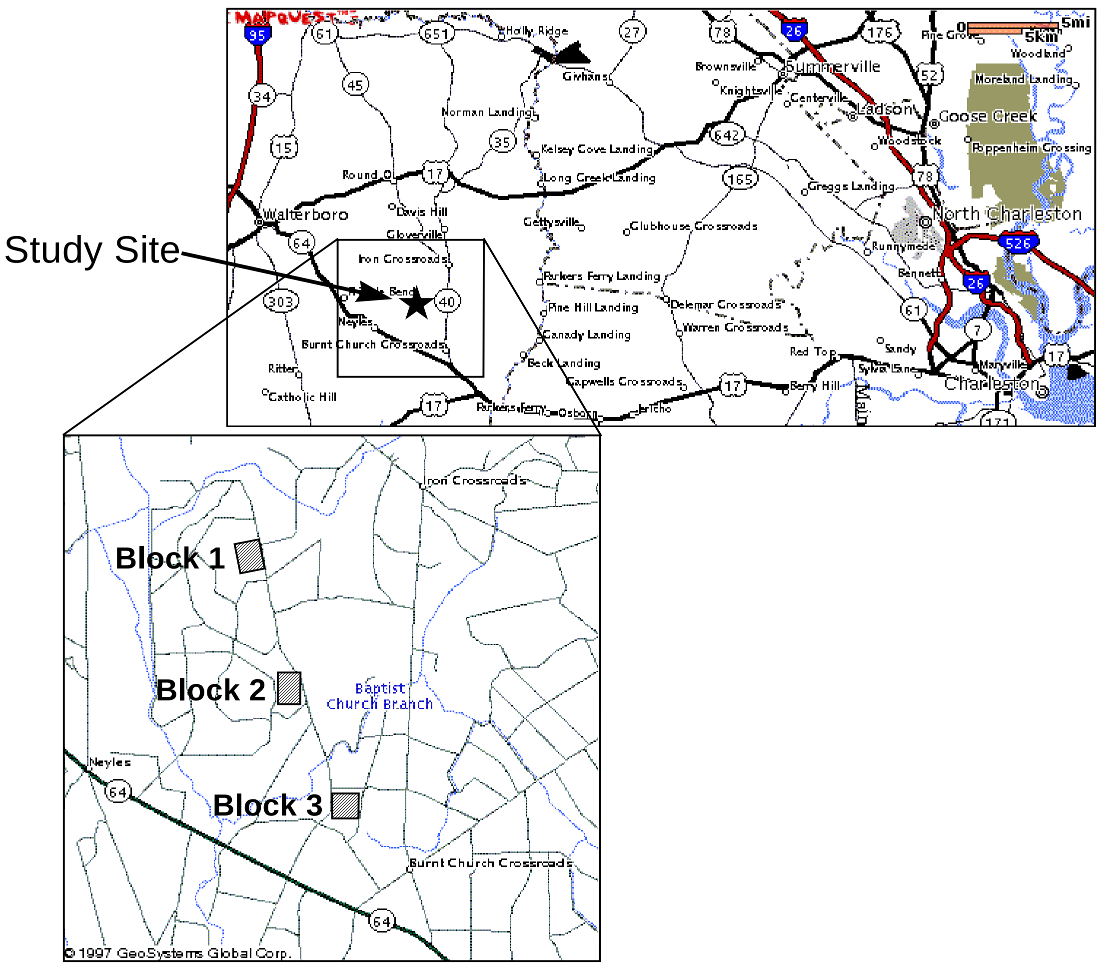
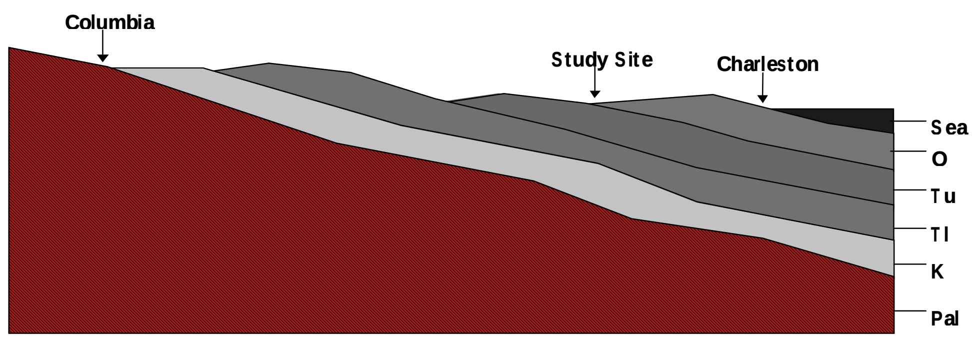


Figure III-1. Study site location map in South Carolina.

Geology

Understanding the underlying geology of a wetland is essential to studying wetland hydrology. The Southeastern Coastal Plain emerged from the sea bottom due to gradual accumulations of marine and river deposits and tectonic movement of the earth (Hunt, 1974) (Figure III-2). Most of the Southeastern Coastal Plain has emerged since the Cretaceous period (70-135 million years before present [MYBP]) (Walker and Coleman 1987), and the present climate and coastline were established about 5,000 years ago (Stout and Marion 1993). Cretaceous period sediment was deposited in the most inland positions, and Quaternary period (2 MYBP) sediment was deposited in the ocean side. Lithology of the sediments were sand, clay, gravel, and marl.



Period	Time	Lithology
Quaternary (Q)	2 Myr	Estuarine and marine gravel
Upper Tertiary (Tu)		River and marine sand, clay and marl
Lower Tertiary	65 Myr	Marine limestone and nonmarine clay and sand
Cretaceous (K)	135 Myr	Sand and clay
[Paleozoic (Pal)]		

(Hunt 1974)

Figure III-2. Geologic cross-section of the central South Carolina Coastal Plain.

A mosaic distribution of xeric and aquic soils in the Southeastern Lower Coastal Plain was formed by geological processes and climate. Gradual accumulation of marine and river sediments formed from unconsolidated sand and clay layers and an impermeable marl layer. Emergence and submergence of the sediments during the most recent glaciation periods and tectonic uplifting developed extended areas of flat topography (slope $\leq 2\%$) in the Southeastern Lower Coastal Plain (Hunt, 1974).

Climate

The climate of the Southeastern Lower Coastal Plain is warm and humid during summer and mild during winter. The average growing season, which is defined as having a daily minimum temperature higher than -2.2°C with a probability of 5 years in 10 years, is March 14 through November 10 (about 240 freeze-free days) (USDA Soil Conservation Service, 1982). Monthly average temperature of the growing season and non-growing season are 21.7°C and 10.2°C, respectively (Table III-1). Average annual precipitation is 1325 mm.

Table III-1. Climatic data at Walterboro, SC.†

Period	Average Temperature	Total Precipitation
	-------- (°C) --------	-------- (mm) --------
April to October	21.7	321
November to March	10.2	1004
Annual	17.8	1325

† Soil Conservation Service, 1982.

Soils

Relatively high rainfall and warm temperature affected surface soil development. Deep sandy soils are often highly leached, acidic, and low in base saturation and nutrient reserve (Buol et al., 1989). Poorly drained soils often have an iron-rich spodic horizon; however, extended periods of high water table cause low site productivity. Soils in the study site are intermediately developed and consist of the Argent and Santee series in Blocks 1 and 3 and the Hobcaw, Nemours, and Yemassee series in Block 2 (USDA Soil Conservation Service, 1982). Taxonomic class descriptions of the soils are listed in Table III-2. Among the soils, Argent is the most common soil in the study site. Alfisols, such as Argent, have well-developed soil profiles and high base saturations (SBS > 35%) (Buol et al. 1989). Eluviation and illuviation of clay caused by gravitational water movement formed a distinctive sandy E horizon and a heavy clay argillic Bt horizon (Buol et al., 1989). The higher soil nutrient status may be the result of slow drainage and the high clay content in the Bt horizon. Drainage classes of these soils are intermediate to very poorly drained, and they are listed as hydric soils in "Hydric Soils of the United States" (USDA Soil Conservation Service, 1991), which is indicated by an 'Aquic' suborder or subgroup of their taxonomic classes (Table III-2). Hydric soil status is one of three required criteria for jurisdictional wetland status.

Table III-2. Soil series names and classification at the study site. †

Soil Series	Taxonomic Class
Argent	Fine, mixed, thermic Typic Ochraqualfs
Santee	Fine, mixed, thermic Typic Argiaquolls
Hobcaw	Fine-loamy, siliceous, thermic Typic Umbraquults
Nemours	Clayey, mixed, thermic Aquic Hapludults
Yemassee	Fine-loamy, siliceous, thermic Aeric Ochraquults

† Soil Conservation Service, 1982.

Ecology

Pine flatwoods are located in the Southeastern Evergreen Forest Region of the Eastern Deciduous Forest (or Temperate Deciduous Forest Biome) (Clements, 1916; Braun, 1950). The pine overstory is maintained by frequent fires (Stout and Marion, 1993). Therefore, the forest is a pyrogenic, stable forest type (fire maintained system). Pond pine (*Pinus serotina* Michx.) is the dominant pine species in natural wet depressions, slash pine (*P. elliottii* Engelm.) is the dominant pine species in slightly wet sites, and loblolly pine (*P. taeda* L.) is the dominant pine species in moist sites. Although fire is less frequent in these moist and wet forests compared to longleaf pine (*P. palustris* Mill.) forests on dryer sites, these forests still require periodic fire for regeneration (Harms et al., 1998; Stout and Marion, 1993).

Typical plant associates in wet pine flats are saw palmetto (*Serenoa repens* (Bartram) Small.), wiregrass (*Aristida stricta* Michaux.), cutthroat grass (*Panicum abscissum*), gallbelly (*Ilex glabra* (L.) Gray), and fern (*Woodwardia virginica* (L.) Smith and *Osmunda cinnamonea* L.) (Abrahamson et al., 1984; Stout and Marion, 1993). The study area is an intensively managed, second-rotation loblolly pine plantation. Common mid- and understory woody vegetation includes sweetgum (*Liquidambar styraciflua* L.), blackgum (*Nyssa sylvatica* Marshall), red maple (*Acer rubrum* L.), green ash (*Fraxinus pennsylvanica* Marshall), oaks (*Quercus* spp.), elms (*Ulmus* spp.), switch cane (*Arundinaria gigantea* (Walter) Muhl.), eastern baccharis (*Baccaris halimifolia* L.), and wax myrtle (*Myrica cerifera* L.) (Burger, 1994).

Project Background

LTSP Project

A long-term cooperative research project, "Sustaining the Productivity and Function of Intensively Managed Forests" (LTSP project), was established among Virginia Polytechnic Institute and State University, Westvaco Corporation, the National Council of the Paper Industry for Air and Stream Improvement, the USDA Forest Service Center for Forested Wetland Research, the USDA Forest Service Timber Harvesting Laboratory, and the U.S. Department of Energy in 1991. The overall objectives of the project were to determine whether or not organic matter removal/redistribution and soil mechanical disturbance from operational logging alter the hydrologic function or damage site productivity, and (assuming alterations occur) to determine if the hydrology and productivity of the disturbed site can be restored by site preparation operations. Under these overall objectives, the following long-term and short-term alternative hypotheses (L-T H_a and S-T H_a, respectively) were formed:

L-T H_a 1: Logging disturbances decrease site productivity.

L-T H_a 2: Mechanical mitigation techniques (mole subsoiling and bedding) restore site productivity damaged by wet-weather logging.

S-T H_a 1: Trafficability can be predicted based on measurable soil productivity.

S-T H_a 2: Logging disturbance adversely changes site hydrology and the spatial and temporal nature of soil drainage.

S-T H_a 3: Logging disturbance adversely alters soil physical, biological, and nutrient supply processes.

S-T H_a 4: Bedding alone mitigates altered hydrologic and nutrient-cycling functioning induced by logging disturbances.

S-T H_a 5: Mole subsoiling in combination with bedding mitigates altered hydrologic and nutrient-cycling functioning induced by logging disturbances.

Overall Study Design

The overall study design is a 2×2 factorial within a completely randomized block design with 3 blocks (Figure III-3). Treatments are dry- and wet-weather harvesting soil disturbances (Dry and Wet, respectively) and bedding and non-bedding site preparation (Bed and Nonbed, respectively). In addition to the four treatment combinations, a no-harvesting and no-site preparation treatment (Control) was added to allow baseline comparisons, and mole subsoiling was added to the wet harvesting with bedding plots to evaluate additional amelioration effects on site hydrology. Each block was carefully located so that soils, topography, and vegetation were relatively homogeneous within a block. Each block is separated by approximately 1.6 km.

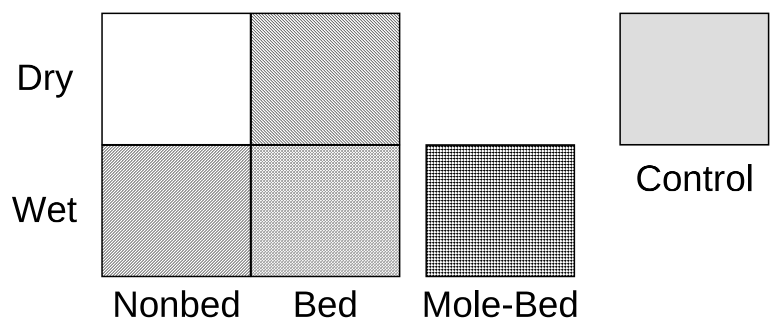


Figure III-3. Schematics of study design.

Six 3.2-hectare treatment plots are randomly located in each block (Figure III-4). The treatments are no-harvesting (Control), dry-weather harvesting with bedding (Dry-Bed), dry-weather harvesting with no bedding (Dry-Nonbed), wet-weather harvesting with bedding (Wet-Bed), wet-weather harvesting with mole channeling and bedding (Wet-Mole-Bed), and wet-weather harvesting with no bedding (Wet-Nonbed).

The study site was identified in fall 1991. The dry-weather harvesting treatment was installed in fall 1993, and the wet-weather harvesting treatment was installed the following winter, 1994. Equipment used for harvesting was rubber-tired fellers with flat shears and medium-sized grapple skidders with standard tire width (about 80 cm or 30 in).

Site preparation treatments, including KG-blading, chopping, mole subsoiling, and bedding, were installed in fall 1995. All harvested plots were sheared and chopped by a D-8 tractor with V-blade and large drum chopper. On the mole subsoiling plots, mole channels were installed at approximately 76 cm (30 in) depth on a 20×20 m grid pattern midway between the well locations by a mole plow (Spoor et al., 1982) pulled by a D-8 tractor. On the bedding treatment plots, beds were created by using a Savannah bedding plow pulled by a D-8 tractor.

One-year-old, genetically improved loblolly pine seedlings were hand-planted in January 1996.

One-meter-deep, perforated, perched-water monitoring wells were installed on a 20×20 m grid throughout the study site in spring 1992 (Figure III-4), and all well points were differentially leveled (using a transit, Philadelphia rod, and engineer's steel tape) for relative horizontal and elevational positions (Elfick et al., 1984). (Each plot has approximately 80 wells.) This well grid system was reestablished after the harvesting and site preparation treatment installations, and all well elevations were again differentially leveled. Surface soil depth (distance between the soil surface and top of the Bt horizon) was also measured at each well point using a 2.5 cm diameter push tube before and after harvesting and after site preparation.

Previous LTSP Studies

Two short-term projects have been completed to answer some of the LTSP hypotheses. Mark A. Burger completed his Master's project, "A Wetland Trafficability Hazard Index Based on Soil Physical Properties and Site Hydrology Evaluations," in 1994 and investigated the first short-term hypothesis (S-T H_a 1): "Trafficability can be predicted based on measurable soil productivity." He found that static soil properties, including bulk density, porosity, texture, and organic matter, were not good indicators for trafficability because those properties were highly variable due to the natural soil heterogeneity, and the processes to acquire those properties were time-consuming. However, dynamic soil properties such as soil moisture content and penetration resistance of the A horizon were good indicators for trafficability because actual equipment ground pressure and soil penetration resistance were highly correlated, soil penetration resistance and moisture content were highly related, and the data were easier to acquire. Based on his observations, he concluded that trafficability hazards were higher at volumetric soil moisture contents greater than 28% even for lightweight equipment; the hazard was low at volumetric soil moisture contents lower than 19% for heavyweight equipment; and the hazard was variable at volumetric soil moisture contents between 19 and 28%, depending on equipment weight and other factors.

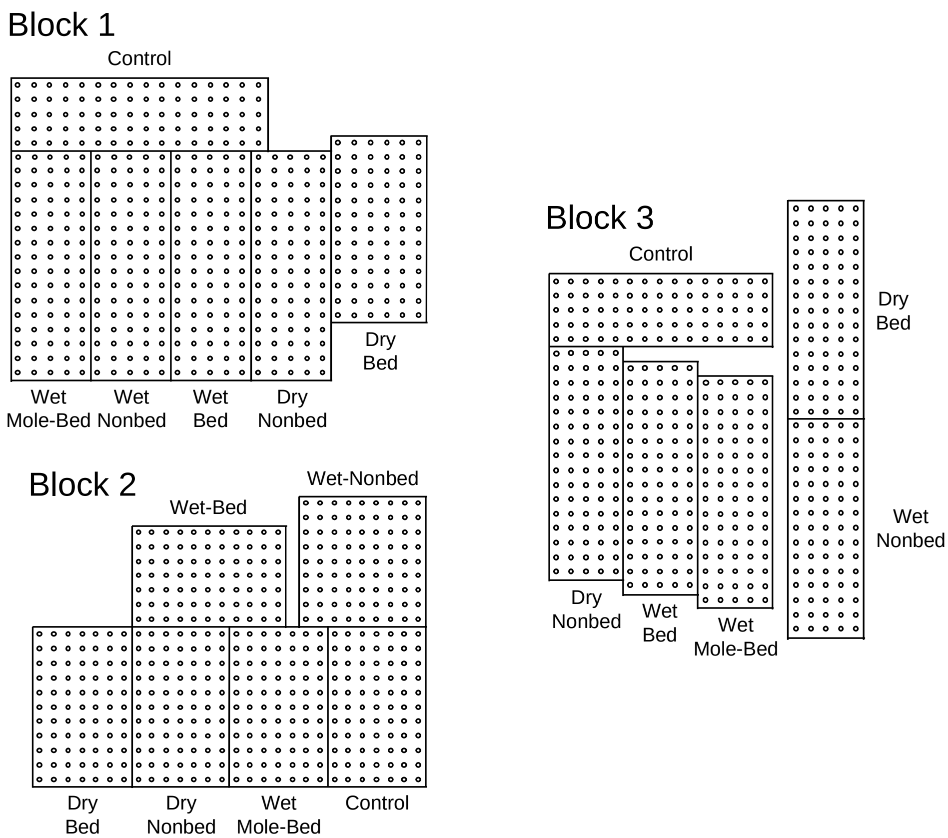


Figure III-4. Treatment plot location in Blocks 1, 2, and 3, and 1-m deep well locations within plots. Treatments include no harvesting (Control), dry-weather harvesting with bedding site preparation (Dry-Bed), dry-weather harvesting with no bedding site preparation (Dry-Nonbed), wet-weather harvesting with bedding site preparation (Wet-Bed), wet-weather harvesting with mole-plowing and bedding site preparation (Wet-Mole-Bed), and wet-weather harvesting with no bedding site preparation (Wet-Nonbed).

David P. Preston completed his Master's thesis project, "Harvesting Effects on the Hydrology and Drainage of Forested Wetlands," in 1996 and investigated part of S-T H_a 2, "Logging disturbance adversely changes site hydrology and the spatial and temporal nature of soil drainage," and S-T H_a 3, "Logging disturbance adversely alters soil physical, biological, and nutrient supply processes." He found that wet-weather logging operations had adverse effects on soil physical properties and site hydrology. Dry-weather harvesting created soil compaction, and less than 10% of the area was affected. Compaction slightly increased bulk density but significantly decreased macroporosity and saturated hydraulic conductivity. Wet-weather harvesting created compaction, shallow and deep ruts, and churns, and more than 75% of the area was disturbed. Compared to undisturbed soils, all disturbed soils showed significantly higher bulk density and lower macroporosity and saturated hydraulic conductivity. He also found that the water tables in the wet-weather harvesting plots during the growing season were higher than those in the dry-weather harvesting plots. He concluded that the higher water tables in the wet-weather harvesting plots were caused by disturbed site hydrology, which was indicated by low macroporosity and saturated hydraulic conductivity of the disturbed areas.

Characterization of Wet Pine Flat Hydrology

Specific Hypotheses

This sub-project was designed to investigate S-T H_a 2: "Logging disturbance adversely changes site hydrology and the spatial and temporal nature of soil drainage;" part of S-T H_a 3: "Logging disturbance adversely alters soil physical, biological, and nutrient supply processes;" part of S-T H_a 4: "Bedding alone mitigates altered hydrologic and nutrient-cycling functioning induced by logging disturbances;" and part of S-T H_a 5: "Mole subsoiling in combination with bedding mitigates altered hydrologic and nutrient-cycling functioning induced by logging disturbances." The following null hypotheses were formed to answer the overall project hypotheses and the first specific objective, to characterize disturbed forest soil morphology and physical properties.

$H_0$1-1: Soil disturbance does not change soil physical properties and morphology.

$H_0$1-2: Site preparation does not ameliorate disturbed soil physical properties and morphology.

$H_0$1-3: Disturbed soil physical properties and morphology do not change with time.

The following null hypotheses were formed to answer the overall project hypotheses and the second specific objective, to assess harvesting and site preparation impacts on the processes that control site hydrology and site productivity.

$H_0$2-1: Harvesting disturbances do not have an effect on surface water storage.

$H_0$2-2: Site preparation does not have an effect on surface water storage.

$H_0$2-3: Surface water and groundwater do not interact.

$H_0$2-4: Soil water storage is not a significant part of water balance.

The following null hypotheses were formed to answer the overall project hypotheses and the third specific objective, to determine effects of harvesting and site preparation on site hydrology, specifically on the overall hydrological balance and on spatial and temporal patterns of surface water storage.

$H_0$3-1: Harvesting does not alter the overall surface water level.

$H_0$3-2: Site preparation does not alter the overall surface water level.

$H_0$3-3: Microsite hydrology is not affected by soil disturbances.

$H_0$3-4: Overall site hydrology is not affected by soil disturbances.

$H_0$3-5: Microsite hydrology is not affected by site preparation.

$H_0$3-6: Overall site hydrology is not affected by site preparation.

$H_0$3-7: Harvesting does not alter the 'wetland status' of wet pine flat sites.

$H_0$3-8: Site preparation does not alter the 'wetland status' of wet pine flat sites.

Measurement Methods

Disturbed Soil Profile Characterization

Despite concerns about soil disturbance effects on site hydrology, detailed characterization of disturbed soil morphology, physical properties, and the recovery processes (natural and artificial restructuring) have not been well documented. This disturbed soil characterization study was conducted in and near the study site. Detailed information on the soil profile examination and horizon characterization procedures are described in the Materials and Methods section of Chapter IV.

Two-year-old deeply rutted soil profiles were described at the severely rutted area of Wet-Nonbed plots in Blocks 1 and 2, two-year-old churned soil profiles were described at the deck area of Wet-Bed plots in Blocks 1 and 2, and bedded soil profiles were described in Wet-Bed plots in Blocks 1 and 2. Undisturbed soil profiles were described in the Control plot in Block 2. Recently created deep-rutted soil profiles were described on similar soils near the study site.

Soil profile descriptions for disturbed soil characterization included evaluation of horizon designation, depth, and soil strength (Bradford, 1986), and soil matrix and mottle colors, texture, structure, moist and wet consistency, internal surface features, concentrations, and horizon boundaries (Buol et al., 1989). Intact soil core and composite soil samples were collected from each designated morphological horizon. Intact soil core samples were used to measure bulk density, macro-, micro-, and total porosity, saturated and unsaturated hydraulic conductivity, and air permeability. A soil structural stability index was calculated from air permeability and water permeability. (Intrinsic permeability was calculated from saturated hydraulic conductivity.) Aggregate stability index, total soil carbon content, and soil particle size values were determined on composite soil samples.

Analysis of variance and paired t-tests (Steel and Torrie, 1980) were used for univariate statistical analysis of each soil physical properties, and multivariate statistical techniques including principal component analysis, factor analysis, and biplots (Johnson and Wichern, 1992; SAS Institute Inc., 1988; MINITAB Inc., 1996) were used to evaluate overall characteristics of disturbed soils. Null hypotheses $H_0$1-1 through $H_0$1-3 were addressed by these detailed soil profile descriptions, soil physical property characterizations, and microsite hydrology characterizations.

Site Hydrology and Water Balance Characterization

Surface water hydrology characterization is very important to the understanding of wetland functions. Surface water fluctuations and storage changes were determined from monthly 1-m well measurement data, and groundwater head changes were determined from piezometer measurement data. Furthermore, monthly precipitation and evapotranspiration were estimated to determine a wet pine flat water balance. Detailed information on measurement methods and determination procedures is presented in the Materials and Methods section of Chapter V.

Monthly soil water storage change was determined as the difference in soil water level between two consecutive monthly measurements because monthly surface water level represents the sum of the input and output of water during a month. Surface water level was converted to an equivalent soil water content by a linear regression equation, which was developed from previous study data (Burger, 1994). The soil water content was transformed to soil water storage based on the average surface soil depth and average total porosity. These analyses were used to address Null Hypotheses 2-1 and 2-2.

Surface water and groundwater interactions were determined from their head differences, and the volume of groundwater in- or outflow through the Bt horizon was calculated by Darcy's Law. Two sets of piezometers were located in each plot, and the plot average of groundwater total head was determined from the piezometer measurements. Plot average of surface water level (head) was determined from monthly surface water level data. Groundwater head and surface water level were used to determine vertical head gradient over the Bt horizon. Saturated hydraulic conductivity of the Bt horizon was measured from the intact soil core samples, and thickness of the Bt horizon was determined from the profile analysis. These surface water and groundwater interaction results addressed Null Hypotheses $H_0$2-3.

In order to characterize the water balance of wet pine flats, other input and output sources were determined. The precipitation component was measured by a tipping bucket rain gage with computerized data recorder at Block 1 and by non-recording rain gages at each block. Potential evapotranspiration was estimated by the Penman Equation (Penman, 1948), Penman-Monteith Equation (Monteith, 1965), and Thornthwaite Equation (Chow, 1964) using meteorological data obtained at the study site. Quantification of surface water lateral flow was very difficult at the study site, since topographic differences within the area are subtle (0%-2% slope). Additionally, existing drainage ditches around the study area collected water from the study site and a much broader adjacent area. Therefore, the surface water lateral flow was calculated as residual (Δ), which was calculated by subtracting the sum of outputs and soil water storage from the sum of inputs. This annual water balance characterization addressed Null Hypothesis $H_0$2-4.

Spatial Characterization of Surface Water Hydrology

Spatial characterization of harvesting and site preparation effects on surface water hydrology included univariate analysis of overall surface water level, spatial analysis of microsite hydrologic gradient vectors, multivariate analysis of surface water level change, and evaluation of predicted surface water level changes with respect to the wetland delineation hydrology criteria. Detailed information on data description and analysis processes is given in the Materials and Methods section of Chapter VI.

Data used in this section were monthly surface water level, relative elevation, and surface soil depth for pre- and post-harvesting and site preparation periods, disturbance class, and automated continuous surface water level measurement data. Disturbance class was a weighted average of qualitative soil disturbance levels within a 10-m radius of a well and was determined at each well point immediately after harvesting (Aust et al., 1998c). Automated surface water monitoring wells were installed in March 1996 at each treatment plot (18 locations), and surface water level was monitored at 4-hour intervals.

Univariate statistical analyses were used to test harvesting, site preparation, or harvesting/site preparation combination effects on measured variables for each treatment based on the randomized complete block design experiment. Analyses for a 2×2 factorial with block design were used for evaluation of harvesting, site preparation, and harvesting $\times$ site preparation interaction effects for the post-site preparation period. Results of these analyses addressed Null Hypotheses $H_0$3-1 and 3-2.

The hydraulic gradient vector and microtopography indices were calculated for each well location by using the relative hydraulic head difference between a well and the four surrounding wells. These values were used to evaluate harvesting and site preparation effects on micro- and block-wide site hydrology.

Multivariate statistical analyses, including principal component analysis, factor analysis, and cluster analysis (Johnson and Wichern, 1992), were used to classify overall harvesting and site preparation effects on surface water level. New variables were generated from monthly surface water level measurement data to represent dynamic properties of site hydrology. Surface water level, site hydrology, soil, topography, and disturbance variables were also included in the multivariate analysis. Spatial characterization of hydraulic gradient and multivariate analysis results addressed Null Hypotheses $H_0$3-3 through 3-6.

Multiple linear regression techniques (Montgomery and Peck, 1992) were used to characterize spatial and temporal surface water dynamics in the study area. First, relationships between monthly surface water table and the temporal, spatial, and physical properties were established by the multiple linear regression method. Then, daily surface water levels at each well point during the 1996 and 1997 growing seasons were predicted based on the multiple linear regression equations. Finally, the predicted daily surface water levels were evaluated with respect to the wetland hydrology criterion (1991 Wetland Delineation Manual proposed revisions), to examine forest harvesting and site preparation effects on site hydrology. These spatial and temporal characterizations should reveal soil disturbance and site preparation effects on site hydrology and addressed Null Hypotheses $H_0$3-7 and 3-8.

CHAPTER IV

MORPHOLOGICAL AND PHYSICAL CHARACTERIZATION OF DISTURBED FOREST SOILS IN THE LOWER COASTAL PLAIN OF SOUTH CAROLINA[4]

Abstract

Wet-site harvesting operations cause severe soil disturbances that may reduce long-term site productivity. Voluntary forestry BMPs have been developed to minimize and ameliorate the disturbances. However, the effects of soil disturbance on long-term site productivity and the effects of amelioration techniques on site hydrology are uncertain. The objectives of this study were to characterize disturbed forest soil morphology and physical properties in order to understand the mechanisms and potential effects on site hydrology and site productivity. The study site is located in an intensively managed loblolly pine plantation in the lower coastal plain of South Carolina. Dry- and wet-weather harvesting treatments were installed in summer 1993, and winter 1994, respectively. Soil profiles were described for recently disturbed deeply rutted areas, 2-year-old deeply rutted and churned areas, bedded areas, and undisturbed soil. Intact soil core samples and composite soil samples were collected from each identified morphological horizon for soil physical characterizations. Soil profile descriptions and soil physical property measurements indicated that a significant amount of organic debris was incorporated in the surface horizons, and the subsurface soil horizons showed significant soil structural changes and increased redoximorphic features caused by soil disturbance. Disturbed subsurface horizons had very low hydraulic properties, which probably caused a high perched water table and slower surface water drainage. The disturbed soil layers in recently created ruts consisted of exposed and severely disturbed soils that had originally been subsurface soils. However, this layer was naturally ameliorated two years after the disturbance. Bedding site preparation had little amelioration effect on the physical properties of surface soil horizons because the disturbed surface horizons already had some incorporation of organic debris. Overall, the main effect of bedding in a disturbed wet site was to increase the aerated soil volume. The bedding appeared to have little effect on disturbed subsurface

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[4] Chapter IV is prepared for submission to *Soil Science Society of America Journal*.

horizons, implying that the effect of soil disturbance may not be reflected by initial tree growth response, but that disturbed soil horizons could affect long-term site productivity.

Introduction

During the 1950's, forest operations became more intensive and mechanized, and forest land managers became concerned about the potential effects of increased traffic and disturbance on long-term forest productivity. Heavy harvesting equipment can cause severe soil disturbances, particularly on wet or moist forest sites. Several forest productivity studies from around the world have indicated that forest productivity decline may occur with certain changes in soil properties. Powers et al. (1990) reviewed reports documenting decreased productivity of Norway spruce (*Picea abies* (L.) Karst) in Europe, radiata pine (*Pinus radiata* D. Don) plantations in Australia, and Scots pine (*P. sylvestris* L.) in eastern Germany. These declines were attributed to organic matter decreases and/or soil compaction that created poor drainage. These soil changes caused nutrient deficiencies and created an imbalance in soil water and air availability.

In the southeastern United States coastal plain, pine flatwood productivity declines have also been reported. Gholz and Fisher (1983) estimated that the growth rate of the original over-100-year-old longleaf pine (*P. palustris* Mill.) was almost twofold that of current slash pine (*P. elliottii* Engelm.) plantations. They concluded that organic matter removals during intensive harvesting and site preparation operations had caused productivity decreases on these flatwood soils (Typic and Ultic Haplaquods). Tiarks and Haywood (1996) evaluated the long-term effects of disking and bedding site preparation on the productivity of first- and second-rotation slash pine plantations in the West Gulf Coastal Plain of Louisiana. They concluded that site preparation in the first rotation limited soil nutrient availability, and first-rotation plantation depleted the nutrients, which caused a decrease in second-rotation pine height.

Earlier researchers recognized that severe disturbance due to harvesting had negative effects on tree growth. Surface soil disturbances by grazing and logging operations on wet, clay-textured soils decreased water and air fluxes in soil, and these created adverse seedling establishment conditions (Person and Marsh, 1935). Youngberg (1959) reported that soil physical and chemical property alterations caused by forest harvesting operations significantly decreased Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedling growth in the northwestern United States. Similar results were also reported for loblolly pine (*P. taeda* L.) seedling survival and growth on severely disturbed wet sites in the southeastern United States (Hatchell et al., 1970; Scheerer et al., 1994).

Harvesting operations on dry soils caused organic matter losses and soil compaction on frequently trafficked areas (Moehring and Rawls, 1970). Organic matter losses cause overall nitrogen-pool decreases in the long term. Soil compaction causes significant bulk density increases and soil aeration decreases, and the low oxygen supply causes low soil mineralization. Therefore, nitrogen-deficient conditions are created by organic matter losses and soil compaction (Youngberg, 1959). Harvesting operations under wet soil conditions caused organic matter losses and soil compaction, puddling, and smearing (Moehring and Rawls, 1970), and these severely disturbed soils significantly altered soil physical properties (Hatchell et al., 1970).

Although numerous studies have characterized compacted agricultural and forestland soils (Hillel, 1982; Pritchett and Fisher, 1987; Marshall et al., 1996), the morphology and physical characteristics of deeply rutted and churned forest soils are not well documented. Burger et al. (1989) found that soil horizons may be severely disturbed in wet skid trails. Aust et al. (1995) compared dry- and wet-weather harvesting effects on soil physical properties in a wet pine flat. They concluded that dry-weather harvesting created soil compaction and subsequent soil physical property changes in primary and secondary skidding trails, while wet-weather harvesting created more severe soil disturbance and complex soil physical property changes, which increased the height of the water table.

Severe disturbances can cause drastic alterations of soil hydraulic properties. Rutted and churned soils have different soil water release patterns compared to undisturbed soils (Jamison, 1963; Gradwell, 1966; Huang et al., 1996). Jamison (1963) conducted a laboratory experiment of disturbed soil physical properties and found that macroporosity and available water holding capacity of puddled soils were significantly lower than those of other disturbed soils. Huang et al. (1996) reported significant decreases of sorptivity and unsaturated hydraulic conductivity after harvesting operations. These laboratory experiments and field studies indicate that puddled soils contain less available water and lower water infiltration rates, both of which create less desirable conditions for seedling growth. Forest soil disturbances produced by heavy equipment are deeper and more severe than pasture soil disturbances, suggesting that heavier equipment may have a more significant effect on soil physical and hydrological properties and future forest productivity.

Soil disturbances, such as compaction, shallow and deep rutting, and churning/ smearing, decrease soil hydraulic properties by decreasing soil macropore spaces, disconnecting soil pores, and roughening microtopography (Aust et al., 1993, 1995). Although these disturbances may occur within a relatively small area, soil disturbance potentially alters site hydrology because it is a dynamic continuous process. Despite the concern about the effect of soil disturbance on site hydrology, detailed characterizations of disturbed soil morphology, physical properties, and the soil recovery processes (natural and artificial restructuring) are not well documented.

Despite concerns among environmental managers and the efforts of many researchers, soil disturbance effects on site hydrology and future forest productivity are still relatively unknown, and harvesting and amelioration techniques on wet sites have not been rigorously evaluated. Detailed characterization of disturbed forest soils is critical for understanding the mechanisms of disturbance and for predicting potential effects on site hydrology and site productivity. The objective of this study was to characterize disturbed forest soil morphology and physical properties in order to understand the mechanisms and potential effects on site hydrology and site productivity.

Materials and Methods

This study was conducted as part of a long-term soil productivity study located in an intensively managed loblolly pine plantation in the lower coastal plain of South Carolina. The area was a typical wet pine flat, and the soils on the site were Argent, Santee, Hobcaw, Nemours, and Yemassee series. The common soils within the study area were Argent (Typic Ochraqualfs). Typical undisturbed soils have a well-developed, heavy-clay argillic Bt horizon at a depth of 30-50 cm and an incipient E horizon just above the Bt (USDA Soil Conservation Service, 1982). Drainage classes of these soils are somewhat poorly to very poorly drained, as indicated by "aquic" suborder or subgroup taxonomic classes, and these soils are considered hydric soils (USDA Soil Conservation Service, 1991).

The study site was established in an intensively managed pine plantation in the lower coastal plan of South Carolina in 1991. Dry- and wet-weather harvesting treatments were installed in summer 1993, and winter 1994, respectively, and bedding site preparation treatments were installed in fall 1995. Details of the study layout and project design are contained in Kelting et al. (1999).

Two-year-old deeply rutted soil profiles were described within the severely rutted areas of the wet-weather harvested/non-bedded plots in Blocks 1 and 2 (Figure III-4). Two-year-old churned soil profiles were described at the deck area of wet-weather harvested/bedded plots in Blocks 1 and 2, and bedded soil profiles were described in wet-weather harvested/bedded plots in Blocks 1 and 2. An undisturbed soil profile was described in the control plot in Block 2, and a recently created deep-rutted soil profile was described on a similar soil near the study site.

This study consisted of three parts: (1) soil profile descriptions for morphological characterization of the disturbed and undisturbed soils; (2) soil physical property characterization for quantitative comparison of the disturbed and undisturbed soils by univariate statistical methods; and (3) soil horizon classification by multivariate statistical methods for overall evaluation of the disturbed and undisturbed soil properties.

Profile Description

Soil profiles were described in soil pits that were approximately 1.5 m deep, 4 m long, and 1.5 m wide. The profile description included designation of master horizons, measurement of horizon depth, soil strength (Bradford, 1986), matrix and mottle colors based on comparison to a Munsell soil color chart, texture, and moist and wet consistency, and observation of structure, internal surface features, chemical concentrations and nodules, and horizon boundaries (Buol et al., 1989). Soil matrix color was described in the moist, rubbed condition. All characteristics were described in the field. Soil profile descriptions were produced from these observations.

Soil Physical Property Characterization

Intact and composite soil samples collected from each designated morphological horizon were analyzed for soil physical properties to evaluate overall soil horizon characteristics. Intact soil core samples were collected with a hammer-driven, double-cylinder soil bulk density sampler (Blake and Hartge, 1986) in both horizontal and vertical directions. The soil core was 5 cm diameter and 5 cm long, and 6 samples (3 horizontal direction and 3 vertical direction) were collected from each horizon. These cores were used for determining bulk density (Blake and Hartge, 1986), and macro-, micro-, and total porosity (Danielson and Sutherland, 1986), saturated hydraulic conductivity (Klute and Dirksen, 1986), unsaturated hydraulic conductivity (van Genuchten, 1980; Kool et al., 1985a), and air permeability (Groenevelt and Lemoine, 1987). The constant head method was used for the samples that had relatively high saturated hydraulic conductivity, while the falling head method was used for the samples whose hydraulic conductivity was less than 0.005 m day^{-1}. Unsaturated hydraulic conductivity of each soil core sample was measured by a one-step outflow procedure using a tempe pressure cell (Cat. No. 1400, Soilmoisture Equipment Co., Santa Barbara, CA) under 0.1 MPa of constant pressure (Kool et al., 1985b). Air permeability was determined with a moist soil core sample (0.1 MPa equilibrated) using a modified tempe pressure cell and air flowmeter (603[E500], Matheson Gas Equipment Technology Group, Montgomeryville, PA) under low, constant air pressure (less than 150 mm Hg), and calculated by the Groenevelt and Lemoine equation (1987), which used pressure difference between inlet and outlet of the tempe cell, air flow rate, sample cross sectional area and length, and air dynamic viscosity.

A soil structural stability index was calculated to evaluate soil structural changes resulting from soil disturbances (Whelan et al., 1995). The soil structural stability index was expressed as a ratio between air permeability and water permeability[5] (k_{air}/k_{water}). Intrinsic permeability depends only on the pore geometry of the soil, and therefore, the less the soil structure is disturbed, the closer the stability index approaches 1 (Whelan et al.,

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[5] Water permeability or intrinsic permeability (k_{water}) was calculated by the following equation (Hubbert 1940):

$$k_{water}=(K\mu)/(\rho_w g)$$

where K is saturated hydraulic conductivity, μ is dynamic viscosity of water (1.31×10^{-3} N sec m^{-2}), ρ_w is density of water (1000 kg m^{-3}), and g is acceleration due to gravity (9.8 m sec^{-2}) (from Freeze and Cherry, 1979).

1995). Mechanical resistance of each horizon was measured using a pocket penetrometer (Bradford, 1986).

Aggregate stability index, total soil carbon content, and soil particle size values were determined on composite loose soil samples that were also collected from each designated soil horizon. The loose soil samples were air-dried, ground, sieved to pass a 2-mm mesh, and homogenized (mixed) prior to the analyses. Soil aggregate stability index was measured by a wet-sieving method (Kemper and Rosenau, 1986). Soil remaining on a 1-mm sieve was wet-sieved by a single-cylinder wet-sieving apparatus (Five Star Scientific, Twin Falls, ID) for 10 minutes with a 1.3-cm stroke length and a 35-cycles min^{-1} interval. The percentage of broken aggregate particles that fell through a 0.26-mm sieve during the wet-sieving process (without sand) was taken as the aggregate stability index. The soil sample was not wetted prior to the wet-sieving process, and the wet-sieving period was determined from preliminary tests on samples to maximize the difference among the samples. Total soil carbon was measured using a high-temperature induction furnace method (Nelson and Sommers, 1982). Soil particle size was analyzed by a hydrometer method (Gee and Bauder, 1986).

Analysis of variance and paired t-tests were used for a univariate statistical analysis of all soil physical properties (Steel and Torrie, 1980).

Multivariate Soil Horizon Classification

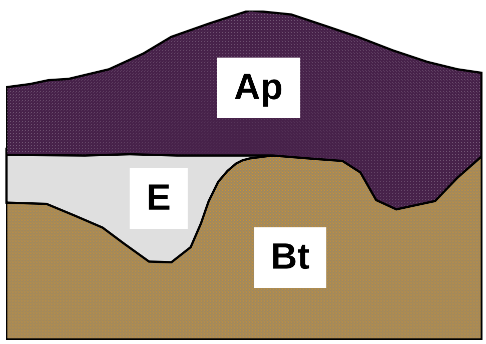
Multivariate statistical methods, including principal component analysis, factor analysis, and biplot (Johnson and Wichern, 1992), were used to evaluate overall characteristics of the soil properties and classify each horizon into specific groups. All statistical analyses were done by SAS (SAS Institute Inc. 1988) and MINITAB (MINITAB Inc., 1996).

Results and Discussion

Soil Profile Description

Undisturbed Soil

The profile of the undisturbed soil was described in a control plot, and this profile consisted of an ameliorated surface horizon having some accumulation of organic materials (Ap), an eluvial horizon (E), and an illuvial (Bt) master horizon (Figure IV-1). The Ap horizon included an old bed that had been created 20 years earlier at stand establishment. The bed had become more consolidated than fresher beds, and no large pores, coarse organic debris, or incorporated subsurface soil fragments were observed; instead, many coarse roots existed in the bed. The boundary between the Ap and E or Bt was clear and irregular, which might have been caused by previous harvesting operations.



Undisturbed

Ap ---- 0-30 cm; black (5YR2.5/1) sandy loam; weak fine granular structure; friable; nonsticky; many fine and many coarse roots; clear irregular boundary.

E ---- 30-43 cm; brown (7.5YR5/2) coarse sandy loam; few fine distinct strong brown (7.5YR4/6) mottles; weak fine granular structure; friable; slightly sticky; few fine roots; clear irregular boundary.

Bt ---- 43-137 cm; brown (10YR4/3) sandy clay loam; common fine distinct red (2.5Y4/8) and strong brown (7.5Y4/6) mottles; moderate medium subangular blocky structure; firm; slightly sticky; few fine roots; few very coarse tubular vertical pores; common faint clay film on face of peds.

Figure IV-1. Soil profile schematics and profile descriptions of undisturbed soil in the lower coastal plain wet pine flats.

The E horizon was discontinuous, and the depth was irregular. It was perhaps reflective of previous harvesting disturbance, because the shape of the E horizon actually resembled a deep tire track. The Bt horizon did not show any evidence of previous disturbance.

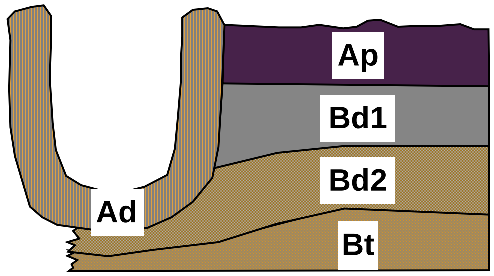
The soil profile in this undisturbed area consisted of irregular to broken boundaries that indicated the severe soil disturbance caused by the prior harvesting operation. However, no soil structural evidence such as stress faces, massive structure, and buried coarse organic matter were observed. This might indicate that a natural restructuring process took place since the last soil disturbance.

Recent Deep Ruts

The soil profile of recently created deep ruts consisted of Ap, Bd1, Bd2, Bt, and Ad master horizons (Figure IV-2). The Ap horizon was a disturbed surface horizon that was well-mixed with organic matter and coarse organic debris. Some coarse debris was compressed beneath the Bd1 horizon because of the surface trafficking that created a wavy to irregular boundary between the Ap and Bd horizons.

The Bd1 horizon was a disturbed subsurface layer that had a higher clay content than the surface horizon and was highly compressed by surface pressure. No evidence of direct soil disturbance such as churning, smearing, or displacement was observed, but the weak to no soil structure was evidence of soil disturbances that were applied during the harvesting operation. Few, fine, prominent redoximorphic features in the horizon indicated slow water conductivity of the horizon and periodic soil saturation.

The Bd2 horizon was a less disturbed subsurface layer similar to the Bd1, except that the texture was more clayey and the structure more intact. The Bt horizon was relatively intact and showed common characteristics of Bt horizons in the region.



Fresh deep ruts

Ap ---- 0-25 cm; very dark gray (10YR3/1) sandy loam; weak fine granular structure; firm; nonsticky; nonplastic; few fine roots; abrupt wavy boundary.

Bd1 ---- 25-51 cm; dark grayish brown (2.5Y4/2) silt loam; few fine prominent yellowish brown (10YR5/6) and gray (10YR5/1) mottles; massive structure with fragments of weak medium subangular blocky and platy; firm; slightly sticky; slightly plastic; few fine roots; clear wavy boundary.

Bd2 ---- 51-76 cm; light yellowish brown (2.5Y6/4) silty clay loam; common medium distinct reddish yellow (7.5YR6/8) and grayish brown (2.5Y5/2) mottles; massive structure with weak medium subangular blocky; friable; slightly sticky; slightly plastic; few fine roots; clear wavy boundary.

Bt ---- 76-102 cm; light olive brown (2.5Y5/4) loam; common medium distinct yellowish red (5YR5/8) and weak red (2.5YR5/2) mottles; moderate fine subangular blocky structure; friable; slightly sticky; slightly plastic; few medium roots; few faint clay film on faces of peds.

Ad ---- olive (5Y5/3) silty clay loam; many coarse prominent yellowish brown (10YR5/8) and grayish brown (2.5Y5/2) mottles; weak medium platy structure; slightly plastic; few very fine roots; clear irregular boundary.

Figure IV-2. Soil profile schematics and profile descriptions of recent deep ruts in the lower coastal plain wet pine flats.

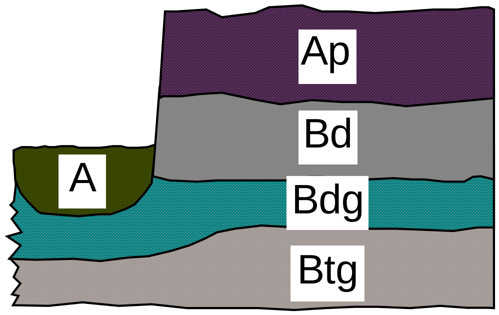
Besides the above master horizons, the recently disturbed soil profile had a severely disturbed soil layer (Ad) along the deep ruts. This churned, compressed, and smeared layer was produced by skidder tractor tires. The layer extended from the soil surface to about 75 cm depth, but the thickness was usually less than 30 cm. The relatively light color of the matrix indicated that the layer was formed mainly from subsurface soil material. Many narrow fissures were also observed among the platy structures. These fissures were probably created by the 2:1-structure clay particles in the soil through the frequent drying and wetting cycles. During the growing season, especially spring, frequent drying and wetting cycles caused shrinking and swelling of the clay particles, and the movement broke weak bounds between the plates. This soil physical property could be very important for soil natural recovery.

The subsurface soil horizons (Bd1, Bd2, Bt, and Ad) did not have strong reduced features. Gleying might not be present because the profile was described shortly after the disturbance, and the soil saturation period might not have been long enough to develop reduced features.

Two-Year-Old Deep Ruts

The soil profile of the 2-year-old deeply rutted soil was described at two locations. Both profiles included Ap, Bdg, Btg, and A horizons, and the horizons present in both profiles had similar properties; therefore, only one of the soil profiles was described in this section (Figure IV-3). The Ap horizon was a disturbed surface layer which consisted of coarse organic debris and fragmented subsurface soils. Incorporated organic debris and clay soil in the horizon were still clearly distinguishable two years after disturbance, which indicated that the recovery process in the horizon was relatively slow.

The Bd horizon was a disturbed, structureless subsurface horizon that included a few fine, prominent redoximorphic features and massive or no structure. The Bdg horizon was a disturbed and reduced subsurface layer that included fragments of weak, medium, platy structure underneath the deep ruts. The platy structures included common, faint, stress surfaces on the surface of the peds, and many coarse, prominent mottles were present in the horizon. These characteristics indicated that the surface disturbance reorganized the soil structure and decreased hydraulic conductivity. The Btg horizon was a thick, relatively undisturbed, reduced, subsurface layer. The prominent mottles and strong gleying in the subsurface horizons (Bd, Bdg, and Btg) indicated that the horizon was saturated for a prolonged period, which was probably caused by the wet-weather harvesting operation, and the subsurface soil had not recovered since the disturbance was created two years before.



Two-year-old deep ruts

Ap ---- 0-8 cm; very dark grayish brown (10YR3/2) silt loam; weak fine granular structure; friable; nonsticky; nonplastic; common very fine roots; clear smooth boundary.

Bd ---- 8-33 cm; dark grayish brown (2.5Y4/2) fine sandy clay loam; few fine prominent strong brown (7.5YR5/8) and gray (N5/0) mottles; massive structure; slightly sticky; slightly plastic; few very fine roots; gradual wavy boundary.

Bdg ---- 33-61 cm; olive (5Y5/3) silty clay; many coarse prominent (5GY5/1) and yellowish brown (10YR5/8) mottles; massive structure with fragments of weak medium platy; slightly sticky; slightly plastic; few very fine roots; common faint stress surfaces on face of peds; gradual wavy boundary.

Btg ---- 61-102 cm; olive (5Y5/3) fine sandy clay; many medium prominent yellowish brown (10YR5/6) and gray (N5/0) mottles; moderate coarse subangular blocky structure; firm; sticky; slightly plastic; few fine roots; few faint clay film on faces of peds.

A ---- very dark grayish brown (2.5Y3/2) loam; weak fine granular structure; nonsticky; nonplastic; common very fine roots; clear irregular boundary.

Figure IV-3. Soil profile schematics and profile descriptions of 2-year-old deep ruts in the lower coastal plain wet pine flats.

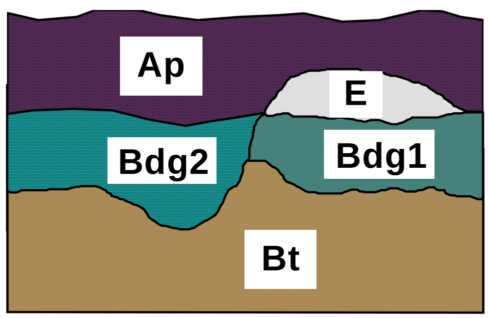
A severely disturbed soil layer (Ad) was not present in the 2-year-old deep ruts. Instead of an Ad horizon, a new A horizon was formed in the bottom of the ruts. The structure was weak, fine, and granular, the consistency was non-sticky and non-plastic, and common, very fine to fine roots were present. These characteristics indicated that the disturbed soil layer (Ad) had been restructured by natural agencies such as shrink-swell clay, wet-dry weather cycle, vegetation roots, and soil organisms since the disturbance occurred.

Two-Year-Old Churn

The profile of a churned soil could be very complex. Repeated trafficking and large amounts of slash disposal in deck areas caused surface soil churning, puddling, and "mud flow," and subsurface soil stress (Figure IV-4). Consequently, two soil profiles described in the 2-year-old churned area were different; one consisted of the Ap, Bdg, and Btg horizons, and the other consisted of the Ap, E, Bdg1, Bdg2, and Bt horizons. The second soil profile is mentioned here to demonstrate the complexity of the churned soil.

The Ap was a disturbed surface horizon including large organic debris and medium-sized subsurface soil materials which were incorporated due to the disturbance. Some large buried logs used for stabilizing the churned soil were observed at the bottom of the Ap horizon. The dark soil matrix color, weak fine granular structure, and friable, non-sticky, and non-plastic soil consistency indicated large amounts of organic matter incorporation in the horizon.

An incipient E horizon was observed in the profile. The horizon was 23 cm thick at the thickest part. The boundary was clear, broken, and the shape of the horizon indicated that the severe soil disturbance interrupted this horizon.



<u>Two-year-old churn</u>

Ap ---- 0-28 cm; black (10YR2/1) sandy loam; weak fine granular structure; friable; nonsticky; nonplastic; many very coarse fine roots; clear irregular boundary.

E ---- 28-51 cm; dark grayish brown (10YR4/2) coarse sand; weak fine granular structure; friable; nonsticky; nonplastic; few medium roots; clear wavy boundary.

Bdg1 -- 51-71 cm; very dark grayish brown (2.5Y3/2) coarse sandy clay loam; few medium distinct yellowish brown (10YR5/6) and very dark gray (5Y3/1) mottles; weak fine granular structure with fragments of weak medium platy; friable; sticky; nonplastic; few fine roots; clear wavy boundary.

Bdg2 --- 60-84 cm; dark olive gray (5Y3/2) coarse sandy loam; moderate medium subangular blocky; slightly sticky; nonplastic; clear irregular boundary.

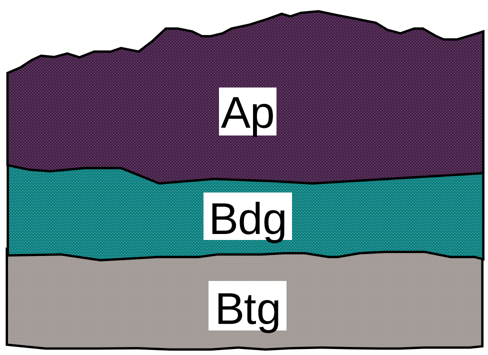
Bt ---- 71-120 cm; olive brown (2.5Y4/4) sandy clay; many medium prominent yellowish red (7.5YR5/8) and dark gray (N4/0) mottles; moderate medium subangular blocky structure; firm; sticky; plastic; few fine roots; few faint clay film on faces of peds.

Figure IV-4. Soil profile schematics and profile descriptions of 2-year-old churn in the lower coastal plain wet pine flats.

The Bdg1 was a disturbed subsurface layer beneath the E horizon. Some slash mixed into the soil was observed in the horizon. The Bdg2 was also a disturbed horizon located in the side of the Bdg1 and slightly deeper section of the profile. A buried log just above the horizon indicated a high degree of stress applied on the horizon. Mottling was not observed in the horizon because the whole Bdg2 was reduced. The Bt was a relatively intact, undisturbed horizon.

Bedded Soil

The profiles of both bedded soils had well-mixed, thick surface soils (bed) and intact subsurface horizons. One of the profiles had a buried original surface horizon (Ap2) under the mounded surface soil (Ap1), and the other profile showed disturbed, subsurface horizons under the surface soil. Since the first profile was relatively undisturbed, the second profile is described here to demonstrate the different bedding effects on surface and subsurface soil horizons (Figure IV-5).



Bedded

Ap ---- 0-43 cm; very dark grayish brown (10YR3/2) coarse sandy loam; weak fine granular structure; very friable; nonsticky; nonplastic; few fine roots; few coarse cylindrical silicate concretions; abrupt irregular boundary.

Bdg ---- 43-69 cm; dark grayish brown (2.5Y4/2) coarse sandy clay; many medium distinct yellowish brown (10YR5/6) and dark gray (10YR4/1) mottles; massive structure; sticky; slightly plastic; few few fine roots; few faint stress faces on faces of peds; gradual wavy boundary.

Btg ---- 69-119 cm; weak red (2.5YR4/2) coarse sandy clay; many coarse prominent dark red (10R3/6), yellowish red (7.5YR5/8), and dark gray (N4/0) mottles; moderate coarse subangular blocky structure; firm; sticky; slightly plastic; few fine roots; few faint clay film on face of peds.

Figure IV-5. Soil profile schematics and profile descriptions of bedded soil in the lower coastal plain wet pine flats.

The profile consisted of Ap, Bdg, and Btg horizons. The Ap horizon was a thick mound of surface soil that consisted of a mixture of disked surface soil, coarse organic debris, and fragmented subsurface soils. This indicated that bedding site preparation effectively produced a large amount of pore space in various sizes, including relatively large pores. These large pores in the 1-year-old bed could cause low seedling survival because of potential seedling root desiccation.

The Bdg was a disturbed, reduced subsurface horizon remaining under the bedded surface soil. Few, faint, stress faces were found in the horizon, which perhaps indicated that the bedding operation not only ameliorated the subsurface horizon, but also applied significant stress on the horizon. The Btg was a relatively intact, reduced, subsurface horizon.

Bedding site preparation is an amelioration technique recommended by BMPs, especially on severely disturbed wet sites, because many bedding studies showed improved seedling growth with a bedding treatment and bedding appears to ameliorate soil disturbance (Terry and Hughes, 1975; Derr and Mann, 1977; Sarigumba and Anderson, 1979; Burger and Pritchett, 1988; Aust et al., 1998). However, this profile description showed no bedding amelioration effect on the physical properties of the disturbed subsurface soil horizons after one year.

The soil profile descriptions revealed that wet-weather harvesting and bedding site preparation caused significant changes in the surface and subsurface horizons (Figures IV-1,2,3,4,5). All disturbed soils contained disturbed surface and subsurface horizons above undisturbed subsurface horizons (Bt or Btg), and E horizons were only observed in a few disturbed soils. Disturbed surface horizons (Ap) typically contained coarse organic debris and fragmented subsurface soils. Surface horizons within the ruts (Ad) were churned, compressed, and smeared. However, the horizon was not observed in the 2-year-old deeply rutted soils, which indicated relatively fast natural soil recovery. Disturbed subsurface horizons (Bd and Bdg) typically had no structure or platy structures. These structures were probably caused by the shear stresses applied by heavy machinery, which physically broke down or reorganized subsurface soil structures. Gleying and/or redoximorphic features were common among the disturbed subsurface horizons because of the few to many distinctive to prominent mottles that developed due to the prolonged soil saturation. These characteristics indicated a change in saturated hydraulic conductivity or internal soil water drainage patterns. Burger et al. (1989) reported similar soil characteristics caused by wet-weather harvesting operations and found severely disturbed subsurface soil horizons under the disturbed surface horizon.

Soil Physical Property Characterization

Soil physical properties were evaluated among the disturbance types (including bedding site preparation) in each horizon. Each soil physical property of the very similar horizons within a soil, such as the Bd1 and Bd2 horizons of the recent deep ruts, Ap1 and Ap2 horizons of the bedded soil, E and Ec horizons of the 2-year-old churn, and Bd and Bdg horizons of the 2-year-old churn, were pooled because they were not significantly different within a soil.

<u>Surface Soil</u>

Although significant alterations of surface soil properties appeared to be produced by wet-weather harvesting and bedding site preparation, the soil physical properties of the Ap horizons showed relatively similar characteristics among the disturbance types (Table IV-1). Disturbed soils commonly have higher bulk density and soil strength and lower total and macroporosity, conductivity, and field capacity than undisturbed soils because of compressed macropore space and disturbed structures. However, the properties of disturbed Ap horizons (fresh and 2-year-old ruts and churn) did not show those disturbed characteristics, and the properties of ameliorated Ap (bed) did not show significant improvement of the properties compare to the disturbed Ap horizons. Rather, bulk density and soil strength in the undisturbed soil were significantly higher, and the total and microporosity, field capacity, and soil moisture content at 0.1 MPa were significantly lower than in the other Ap horizons. Saturated hydraulic conductivity was also lowest in the undisturbed Ap horizons, although it was not significantly different because of the high variance of the data. These results indicated that soil physical movement caused by forest operations actually improved the soil physical properties of the Ap horizon.

Table IV-1. Physical properties of the disturbed soils.

Disturbance	Bulk Density	Total Porosity	Macro-porosity	Micro-porosity	Saturated Conductivity	Unsaturated Conductivity†	Intrinsic Air Permeability‡	Stability Index§	Field Capacity¶	Moisture Content#	Soil Strength††	Aggregate Stability Index	Total Carbon	Sand	Silt	Clay
	Mg m^{-3}	------------- Ratio -------------			m day^{-1}	µm day^{-1}	*pico* m^2	Ratio	------ g cm^{-3} ------		kg cm^{-2}	------------------------- % -------------------------				
<u>Ap Horizon</u>																
Undisturbed	1.27 ‡‡c	0.41 c§§	0.05 a	0.36 c	0.736 a	7.06 a	0.169 a	1.20 a	0.228 c	0.232 c	1.83¶¶ c	n/a	n/a	n/a	n/a	n/a
Fresh Ruts	1.05 b	0.45 c	0.04 a	0.41 bc	2.602 a	3.96 b	0.167 a	12.78 b	0.386 bc	0.395 b	1.61 c	46.5## ab	3.5 b	25†††	57	18
2-yr Deep Ruts	1.16 bc	0.46 bc	0.05 a	0.41 bc	2.101 a	5.63 ab	0.178 a	0.59 a	0.324 bc	0.303 bc	0.93 ab	47.8 ab	2.1 c	59	21	20
2-yr Churn	0.78 a	0.61 a	0.07 a	0.55 a	12.195 a	6.15 ab	0.214 a	0.04 a	0.726 a	0.672 a	1.10 b	59.9 a	4.8 a	52	25	24
Bed	1.12 bc	0.54 ab	0.06 a	0.49 ab	11.147 a	6.92 a	0.174 a	0.36 a	0.419 b	0.372 b	0.52 a	27.2 b	1.7 c	71	17	13
<u>Ad and A Horizons in Ruts</u>																
Fresh Ruts	1.45 b	0.35 b	0.01 b	0.34 b	0.010 a	2.86 b	0.093 b	27.01 a	0.228 b	0.224 b	1.76 b	34.7 a	0.4 b	16	57	28
2-yr Deep Ruts	1.10 a	0.51 a	0.04 a	0.47 a	3.316 a	9.78 a	0.247 a	0.66 a	0.401 a	0.424 a	0.30 a	32.6 a	1.7 a	62	19	19
<u>E Horizon</u>																
Undisturbed	1.39 a	0.39 a	0.10 a	0.29 a	0.783 a	4.32 a	0.192 a	0.21 a	0.177 a	0.147 ab	2.61 b	n/a	n/a	n/a	n/a	n/a
2-yr Deep Ruts	1.49 b	0.34 ab	0.02 c	0.33 a	0.099 a	3.09 a	0.192 a	4.07 a	0.201 a	0.200 a	3.71 c	56.0 a	1.2 a	57	27	16
2-yr Churn	1.54 b	0.34 ab	0.06 b	0.28 a	0.888 a	5.66 a	0.171 ab	2.56 a	0.159 a	0.142 ab	4.47 d	n/a	n/a	n/a	n/a	n/a
Bed	1.53 b	0.32 b	0.02 c	0.30 a	0.601 a	3.05 a	0.130 b	7.08 a	0.173 a	0.127 b	1.32 a	12.7 b	0.3 b	71	19	11
<u>Bd Horizon</u>																
Fresh Ruts	1.46 a	0.35 a	0.01 a	0.34 a	0.008 a	1.97 b	0.178 a	57.19 a	0.225 a	0.218 a	2.05 b	34.1 a	0.4 a	16	56	28
2-yr Deep Ruts	1.47 a	0.36 a	0.02 a	0.34 a	0.003 a	4.79 a	0.211 a	93.14 a	0.221 a	0.217 a	0.99 a	21.6 a	0.5 a	59	15	25
<u>Bdg Horizon</u>																
2-yr Deep Ruts	1.27 a	0.43 a	0.01 b	0.42 a	0.554 ab	4.64 a	0.145 a	54.31 a	0.325 a	0.322 a	0.84 a	41.4 a	0.4 b	41	14	45
2-yr Churn	1.40 b	0.37 b	0.03 a	0.35 b	0.430 b	6.75 a	0.197 a	34.71 a	0.231 b	0.213 b	1.62 b	34.4 b	1.1 a	59	15	27
Bed	1.42 b	0.37 b	0.01 b	0.36 b	1.608 a	2.07 a	0.165 a	0.17 a	0.248 b	0.245 b	1.13 a	35.6 ab	0.4 b	52	13	35
<u>Btg Horizon</u>																
Undisturbed	1.32 ab	0.41 a	0.04 a	0.37 a	0.420 a	6.67 a	0.163 ab	1.89 a	0.260 ab	0.248 ab	2.33 c	n/a	n/a	n/a	n/a	n/a
Fresh Ruts	1.25 a	0.41 a	0.03 b	0.39 a	0.049 b	4.75 a	0.183 a	62.65 b	0.298 a	0.290 a	1.56 ab	71.3 a	0.3 b	13	34	53
2-yr Deep Ruts	1.42 c	0.37 a	0.01 c	0.36 a	0.008 b	6.17 a	0.094 b	31.08 ab	0.248 ab	0.246 ab	1.34 a	28.9 c	0.4 b	50	12	39
2-yr Churn	1.39 bc	0.38 a	0.03 ab	0.35 a	0.333 ab	4.90 a	0.178 a	12.14 a	0.239 b	0.231 b	1.71 ab	50.5 b	0.6 a	54	15	32
Bed	1.32 ab	0.39 a	0.02 bc	0.37 a	0.267 ab	2.66 a	0.142 ab	35.34 ab	0.274 ab	0.273 ab	1.89 b	47.5 b	0.4 b	49	13	38

† Unsaturated hydraulic conductivity is determined under 0.1 MPa constant air pressure.
‡ Soil water potential of the sample is 0.1 MPa, and pico $=10^{-12}$.
§ Stability index is a ratio of an intrinsic air and water permeability (kair/kwater).
¶ Gravimetric moisture content at 0.03 MPa water potential.
# Gravimetric moisture content at 0.1 MPa water potential.
†† Gravimetric moisture content of soil at measurement time is approximately 15% for surface soils and 18 to 26 % for subsurface soils.
‡‡ Values of bulk density, porosity, saturated- and unsaturated hydraulic conductivity, air permeability, stability index, field capacity, and moisture content are means of 6 samples.
§§ Means followed by the same letter within a column and soil horizon are not significantly different according to Fisher's LSD at a 0.05 probability level.
¶¶ Values of soil strength are means of 6 measurements.
Values of aggregate stability index and total carbon are means of 2 measurements.
††† No statistical analysis is conducted because of no replication of measurement.

Improvement of surface soil physical properties by bedding site preparation appeared to be small. Most of the properties of the bedded Ap horizon were intermediate among the other Ap horizon properties, except soil strength and sand content. The soil strength was lowest because of the tilling, and the high sand content was probably due to the bedding, which mixed the Ap and E horizons. Despite the minor soil physical property differences among the Ap horizons, overall soil characteristics were similar. Unsaturated hydraulic conductivity, air permeability, and stability index results indicated a similarity among the horizons because dynamic properties tend to reflect all physical characteristics.

Severely disturbed churned soil showed significantly higher microporosity than other soils. This was probably caused by higher incorporation of subsurface mineral soil and a repeated kneading process. However, the significantly lower bulk density and higher total carbon content and saturated conductivity indicated that the churned soil had large amounts of organic matter, which probably increased the field capacity, 0.1 MPa moisture content, and aggregate stability index.

The soil layers within ruts were significantly different between recently created ruts and 2-year-old ruts (Table IV-1). The severely disturbed layer in the recent ruts (Ad) had significantly higher bulk density and soil strength and lower porosity, conductivity, field capacity, 0.1 MPa moisture content, soil strength, and total carbon than those of deposited layers in the 2-year-old ruts (A). Although saturated hydraulic conductivity and stability index were not significantly different, those values also showed that the Ad horizon was more disturbed than the A horizon. More herbaceous roots were observed in the profile of the A horizon than in that of the Ad horizon. These results suggested that the soil structural improvements were produced by herbaceous roots and the associated soil organisms. The soil profile description showed many narrow fissures in the Ad horizon, which were caused by 2:1 clay particles (Figure IV-2). These soil profile and physical property results indicated that the Ad horizon was quickly weathered and deposited in the bottom of the ruts by the soil mineralogical properties and the weather, and the deposited A horizon was restructured by biological activities. Sand and silt content of A horizons indicated a gain and loss of sand and silt, respectively, since the disturbance. Sand might have increased because of runoff from the surrounding areas, and silt might have decreased because of surface water outflow.

Soil disturbance could have a significant impact on the E horizon (Table IV-1). Disturbed E horizons had significantly higher bulk density and lower total and macroporosity than those of undisturbed E horizons. These compacted characteristics were produced by pressures and stresses applied by the heavy machinery. However, the other properties were no different or amounted to minor differences among the horizons. Sandy soil is generally resistant to soil disturbance (McKee et al. 1985) because the larger soil particle size enhances soil internal drainage and retains relatively high hydraulic properties after disturbance. However, because of the small internal surface area, water-absorbing capacity and liquid limit of sandy soils are low (Sowers, 1965), making the soil more susceptible to soil disturbances under wet conditions. Wet sandy soil quickly loses resistance and liquefies. This might explain why highly disturbed E horizons were not identified in the soil profiles, since liquefied sand was easily mixed with the other soil.

Although surface soil disturbances were visually severe, soil physical property results indicated that the Ap horizons were not strongly affected by the disturbance. Severe compaction was probably offset by incorporation of organic matter during wet-weather harvesting. In contrast, the soils within ruts (Ad horizons) showed severe physical property alteration. These Ad horizons were compacted, churned, and smeared, which impeded surface water flow and infiltration. However, Ad horizons recovered naturally within two years after the disturbance. The E horizons were extremely susceptible to soil disturbance when the horizons were wet. These results were not in full agreement with other studies conducted in similar forest systems (Pearson and March, 1935; Youngberg, 1959; Moehring and Rawls, 1970; Hatchell et al., 1970; Aust et al., 1993, 1995). Significant negative soil physical property changes of surface soils that had been reported by those studies were perhaps focused on the exposed, disturbed subsurface soils, like the Ad horizon in this study. However, since the Ap and Ad horizons were distinctly different, there is a need for clear distinctions between these horizons in order to characterize disturbed soil properties and to prevent severe soil disturbance.

Subsurface Soil

Differences in subsurface soil physical properties within a horizon were relatively small compared to differences in the surface soil horizons (Table IV-1). The reason was probably that the subsurface horizon contained relatively high amounts of clay; therefore, the physical properties were stable. The bulk density of the Bt horizon prior to harvesting was 1.45 Mg m^{-3}, and total, macro-, and microporosity in the same time was 47%, 6.1%, and 40.5%, respectively (Burger, 1994).

The Bd horizon was the disturbed horizon, which was observed at the upper part of the subsurface horizon. Therefore, the Bd horizon was only found in the disturbed soils. Most of the soil physical properties of the fresh deep ruts and 2-year-old deep ruts were similar. Both horizons had high bulk density (> 1.45 Mg m^{-3}) and low macroporosity (< 2%) and saturated conductivity (< 0.01 m day^{-1}). Unsaturated conductivity of 2-year-old deep ruts was significantly higher than that of fresh deep ruts. This might indicate that a natural amelioration process was initiated in the horizon two years after the disturbance. Soil strengths of the 2-year-old ruts were significantly lower than those of the fresh ruts. This was probably caused by different soil moisture conditions. Soils in the fresh ruts were not saturated when the soil strength was measured. These results indicated that soil properties of the Bd horizon had not changed since the disturbance occurred, and natural soil restructuring processes were very slow in the subsurface horizon.

Bdg horizons were disturbed and saturated subsurface horizons usually found between the Bd and Btg horizons (Figures IV-3, 4, 5). Physical properties of the 2-year-old deep ruts showed significantly lower bulk density and soil strength and higher total and microporosity, field capacity, and 0.1 MPa moisture content than those of churned and bedded soils. These significant differences might be due to traffic frequency. The Bdg horizon in churned and bedded soils probably experienced higher numbers of traffic passes. However, other soil physical property results indicated that differences among the disturbance types were small. Saturated hydraulic conductivity values of the Bdg horizon were higher than those of the Bd horizon, yet the Bdg had reduced characteristics. This might indicate an endosaturation pattern of the soil (saturation from below). Groundwater might flow from a deeper horizon to the surface. However, the water movement was impeded or slowed by the above Bd horizon, thus the Bdg horizon was saturated for a prolonged period and developed strong reduced properties.

Differences in the physical properties in Btg horizons were small, but the differences showed some evidence of disturbance. Physical properties of undisturbed soil had significantly higher macroporosity, saturated hydraulic conductivity, and soil strength, and lower and stable stability index. These results indicated that the Btg horizons were compacted by surface trafficking. Reaves and Cooper (1960) also found that strong soil compacting forces (152 kPa) could compact soil deeper than 100 cm. Strong redoximorphic features in these horizons were probably caused by soil compaction and prolonged saturation period.

Although statistical comparisons among the subsurface horizons were comparing horizons that are physically different by definition, the comparisons clearly showed the soil disturbance effect. Bd horizons had relatively higher bulk density than Bdg and Btg horizons, because the Bd horizon received higher pressure than did the deeper horizons. This was also indicated by the lower macroporosity and saturated and unsaturated hydraulic conductivity of Bd horizons compared to those of Btg horizons. The soil profile descriptions revealed that the structures of the Bd and Bdg horizons were massive or weak platy because of stress and vibration applied by heavy machinery, whereas the Btg horizons had subangular blocky structure with abundant clay films. These soil physical property and profile description results indicated clear evidence of subsurface soil disturbance created by wet-weather harvesting and very slow natural recovery processes.

Directional Hydraulic Properties

Soil disturbance reorganized soil structures and altered many soil physical properties in the surface and subsurface horizons. One of the main concerns about soil disturbances was the potential effect on site hydrology. Previous studies showed an altered site hydrology by disturbed soil physical properties and rough soil surface as the result of wet-weather harvesting (Aust and Lea, 1992; Aust et al., 1993, 1995). Therefore, directional hydraulic properties were examined to evaluate soil disturbance effects on surface water infiltration and perched water lateral flow. Vertical soil core samples were taken perpendicular to the soil surface to measure vertical water flow (infiltration and percolation), and horizontal soil core samples were taken parallel to the soil surface to measure horizontal (lateral) water flow.

Vertical and horizontal air permeability in the fresh deep ruts' Ad horizon were significantly different (Table IV-2). The horizontal air permeability was higher than the vertical air permeability, which indicated that infiltration of standing water in deep ruts was restricted. Saturated and unsaturated hydraulic conductivity of the Ad horizon also showed a similar trend. This impeding effect of the Ad horizon might not be significant in the long term because the Ad horizon was not identified in 2-year-old deep ruts.

Vertical flow of the Bd horizons' saturated and unsaturated hydraulic conductivity and the E horizons' unsaturated hydraulic conductivity were slightly lower than those of horizontal flow, although they were not statistically different (Table IV-2). These trends showed that vertical percolation of perched water might be slowed by Bd and E horizons. These impeding horizons could cause prolonged surface soil saturation after severe soil disturbance.

Table IV-2. Vertical and horizontal directional saturated and unsaturated hydraulic conductivity and air permeability in each designated horizon.

	Saturated Hydraulic Conductivity		**Unsaturated Hydraulic Conductivity**		**Intrinsic Air Permeability**	
Horizon	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**
	---------- m day^{-1} ----------		---------- μm day^{-1} ----------		---------- *p*m^{2}†----------	
Ap	7.429 a‡	6.961 a	6.506a	5.719 a	0.174 a	0.191 a
Ad	0.009 a	0.011 a	2.833 a	2.883 a	0.352 b	0.152 a
A	4.924 a	1.707 a	11.700 a	8.240 a	0.224 a	0.277 a
E	0.719 a	0.585 a	3.963 a	5.008 a	0.164 a	0.171 a
Bd	0.002 a	0.010 a	2.800 a	3.018 a	0.188 a	0.189 a
Bdg	0.880 a	0.461 a	7.478 a	3.711 a	0.185 a	0.165 a
Btg	0.148 a	0.272 a	5.319 a	4.511 a	0.126 a	0.167 a

† *pico* = 10^{-12}.
‡ Means followed by the same letter within a row and variable are not significantly different according to Fisher's LSD at 0.05 probability level.

Multivariate Soil Horizon Classification

Univariate analyses provided evidence of soil disturbance and disturbance effects on surface and subsurface soil horizons. However, evaluation of overall soil disturbance effects on soil was difficult because interpretation of the univariate results involved synthesis of all variables, which were strongly correlated to each other (Table IV-3). For example, surface soil void-related properties, such as bulk density, porosity, saturated hydraulic conductivity, field capacity, and 0.1 MPa moisture content, showed relatively high correlations, but conductivity-related properties, such as saturated and unsaturated hydraulic conductivity and air permeability, only showed moderate correlations. A number of subsurface properties, including unsaturated hydraulic conductivity, air permeability, stability index, soil strength, aggregate stability index, and total carbon content, did not show any significant correlations. These complex relationships among the physical properties were difficult to interpret.

Multivariate analysis is a useful technique for evaluating the overall effects of objects that have many different properties with less bias and for quantifying the actual differences (Johnson and Wichern, 1992). Therefore, multivariate statistical methods were used to characterize the disturbed and undisturbed soil properties, although the balance of this data matrix (observations by variables) was not ideal for the statistical analysis. All intact soil core soil physical property results were used for principal component analysis and factor analysis to characterize the disturbance and amelioration effects. All raw data variables were normalized and standardized to 0 with 1 standard deviation prior to the analysis, so that each variable had equal influence. Then the variable weights and observation scores of each factor were plotted on a biplot for overall interpretation. Surface soil horizons, including the Ap, Ap1, Ap2, and A horizons, and subsurface soil horizons, including the Bd, Bdg, Btg, Bt, and Ad horizons, were analyzed separately because they were different soils. The Ad horizon (a soil layer in the recent deep ruts) was analyzed with subsurface soil horizons because it was exposed subsurface soil. The E horizon was not analyzed because the differences among the disturbance types were very small.

Table IV-3. Pearson correlation coefficients of surface and subsurface soil physical properties†.

Sub-Surface Soil \\ Surface Soil	Bulk Density	Total Porosity	Macro-porosity	Micro-porosity	Saturated Conductivity	Unsaturated Conductivity	Intrinsic Air Permeability	Stability Index	Field Capacity	Moisture Content	Soil Strength	Aggregate Stability Index	Total Carbon	Sand	Silt	Clay
Bulk Density		-0.771	-0.767	-0.670	-0.702	-0.196	-0.577	0.521	-0.912	-0.879	0.372	-0.471	-0.886	-0.259	0.307	0.011
Total Porosity	-0.943		0.543	0.979	0.822	0.226	0.365	-0.639	0.880	0.766	-0.367	0.367	0.484	0.611	-0.606	-0.384
Macro Porosity	-0.173	0.176		0.359	0.666	0.418	0.625	-0.718	0.554	0.485	-0.499	0.516	0.669	0.562	-0.608	-0.200
Micro Porosity	-0.838	0.892	-0.288		0.751	0.148	0.252	-0.534	0.843	0.732	-0.286	0.275	0.366	0.555	-0.533	-0.399
Saturated Conductivity	-0.124	0.239	0.223	0.130		0.210	0.309	-0.463	0.119	0.149	-0.421	0.423	0.395	0.518	-0.491	-0.394
Unsaturated Conductivity	0.141	-0.130	0.324	-0.275	-0.250		0.817	-0.551	-0.272	-0.311	-0.597	-0.266	-0.120	0.647	-0.705	-0.215
Intrinsic Air Permeability	0.021	-0.041	0.223	-0.144	-0.081	-0.063		-0.529	-0.116	-0.251	-0.687	-0.041	0.356	0.457	-0.546	-0.002
Stability Index	-0.011	-0.089	-0.475	0.131	-0.637	0.114	0.434		0.145	0.079	0.466	-0.476	-0.327	-0.899	0.896	0.549
Field Capacity	-0.919	0.909	-0.193	0.973	0.772	0.037	0.357	-0.391		0.935	-0.230	0.429	0.784	0.192	-0.245	0.042
Moisture Content	-0.881	0.882	-0.222	0.960	0.619	-0.091	0.283	-0.318	0.983		-0.246	0.375	0.776	0.032	-0.093	0.166
Soil Strength	0.312	-0.301	0.487	-0.514	-0.033	0.006	-0.053	-0.431	-0.509	-0.492		-0.012	-0.172	-0.732	0.804	0.221
Aggregate Stability Index	-0.479	0.361	0.673	0.241	0.255	-0.076	0.080	-0.241	0.335	0.295	0.166		-0.027	0.363	-0.287	-0.450
Total Carbon	0.034	-0.122	0.008	-0.127	-0.125	0.253	0.629	0.450	-0.083	-0.250	-0.326	0.562		-0.048	0.034	0.072
Sand	0.139	-0.080	-0.021	-0.078	0.137	0.365	0.001	-0.034	-0.120	-0.142	-0.402	-0.074	0.337		-0.971	-0.689
Silt	0.269	-0.342	-0.102	-0.327	-0.241	-0.355	0.229	0.187	-0.292	-0.293	0.504	-0.168	-0.060	-0.861		0.496
Clay	-0.772	0.796	0.232	0.765	0.192	-0.032	-0.432	-0.289	0.778	0.824	-0.180	0.459	-0.532	-0.293	-0.233	

† Surface and subsurface soils are analyzed separately. E and C horizons are excluded from this analysis.

Principal Component Analysis and Factor Analysis

Surface Soil Horizon

Principal component analysis was used to evaluate the importance of each variable and their relations. Principal component analysis creates the same number of new axes (principal components or PCs) as number of variables. Principal components are orthogonal to each other and are positioned to maximize variance of observations along the axes. Eigenvalues of each PC indicate an importance of each PC with respect to overall data variances. Therefore, a high eigenvalue indicates high importance of a PC. A scree plot is commonly used to evaluate PCs, and a PC whose eigenvalue is larger than 1.0 is considered to be useful for data explanation (Johnson and Wichern, 1992). Each eigenvalue consists of different weights of raw data variables. These variable weights indicate contribution of each variable to the PC.

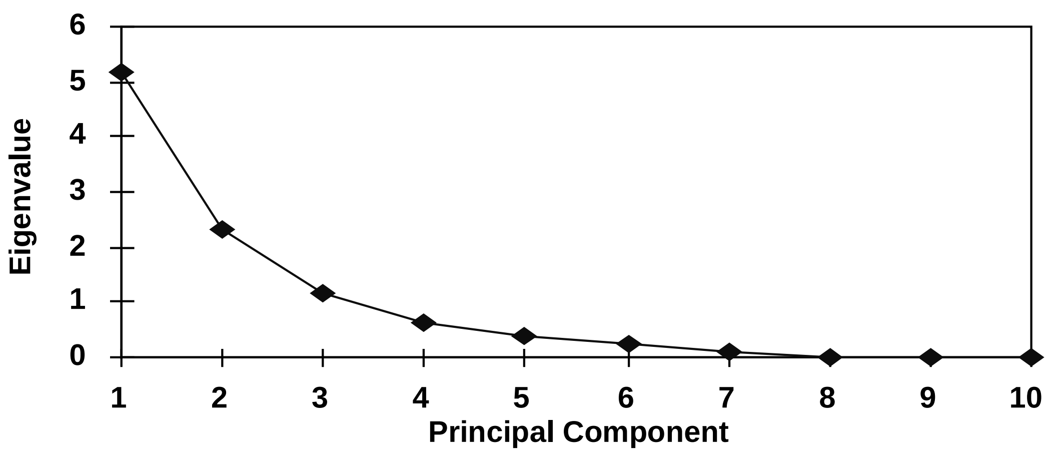
Overall eigenvalues of a principal component analysis showed that PCs 1 and 2 explained 74.9% of overall variability of the data (Figure IV-6). PC 1 consisted of high weights ($|\lambda| > 0.70$) of bulk density, total and microporosity, field capacity, 0.1 MPa moisture content, and saturated conductivity. Since these soil physical properties were related to soil void space and soil structure, PC 1 was an explainable, important factor. PC 2 consisted of high weights of unsaturated conductivity, air permeability, and soil strength. These properties were explaining soil structural resistance or tortuosity. The other PCs explained about 25% of overall variability, but they did not consist of high variable weights ($|\lambda| > 0.50$), except macroporosity in PC 3 (-0.72), and their eigenvalues were less than 1.0. Therefore, principal component analysis reduced the number of variables to two explainable PCs. These results also indicated that soil void space and soil structural resistance were important measurements in evaluating surface soil property.

Factor analysis rotates variables around an origin of principal components to polarize variance of the variables along the axes. Since the rotation method used in this analysis ('varimax' method) was linear, the relations among the variables did not change, and each axis remained orthogonal. (Principal component axes were now called factor axes because all variable weights were rotated.)

This variance-maximizing-rotation process slightly improved the balance between Factors 1 and 2 (Table IV-4). Orthogonal transformation matrix of this rotation process was:

$$T = \begin{bmatrix} 0.97985 & 0.19976 \\ -0.19976 & 0.97985 \end{bmatrix}$$

Weights of total and microporosity, field capacity, and 0.1 MPa moisture content in Factor 1 were improved, while these variables' weights in Factor 2 were decreased. The weights of bulk density and saturated hydraulic conductivity in Factor 1 were kept relatively high. The weights of air permeability and soil strength in Factor 2 were also improved by the rotation. Scores of each observation were calculated from the factor loading (weight of each variable) for later biplot analysis.



PC	1	2	3	4	5	6	7	8	9	10
BD	-0.90936	0.00093	0.23620	0.33060	-0.05133	0.05301	-0.01560	0.04524	0.01549	0.00042
TotalP	0.90808	-0.12546	0.30275	0.21211	0.06008	0.12817	-0.04747	0.02549	-0.00753	0.00283
MacroP	0.54023	0.30407	-0.71912	0.03606	0.11911	0.28637	-0.02517	0.02055	0.00386	-0.00056
MicroP	0.83116	-0.19594	0.46296	0.21716	0.03951	0.07115	-0.05048	0.01060	-0.00201	-0.00313
FC	0.95823	-0.16541	0.16206	-0.13663	0.05312	0.01350	-0.05238	-0.05936	0.01523	0.00071
MC	0.85807	-0.31137	0.06089	-0.29091	-0.21946	0.00944	0.16676	0.04844	0.00432	-0.00004
Ksat	0.79775	0.09157	-0.31724	0.32382	0.18952	-0.33390	0.04493	0.01637	0.00274	0.00006
Kunsat	-0.03791	0.89200	0.34144	0.07363	0.19857	0.09909	0.17648	-0.02250	0.00016	0.00003
Kair	0.20679	0.86082	0.21015	-0.37032	0.07168	-0.10898	-0.12656	0.04347	0.00167	-0.00005
Strength	-0.45807	-0.70255	0.09040	-0.23935	0.47914	0.02269	0.02491	0.02078	0.00070	-0.00004

Figure IV-6. Scree plot of principal component eigenvalues for surface soil physical properties and the variable weights for each principal component. Soil physical property variables are bulk density (BD), total, macro-, and microporosity (TotalP, MacroP, and MicroP, respectively), field capacity (FC), 0.1 MPa soil moisture content (MC) saturated and unsaturated hydraulic conductivity (Ksat and Kunsat, respectively), air permeability (Kair), and soil strength (Strength).

Table IV-4. Surface soil physical property weights for principal components (PCs) 1 and 2 and Factors 1 and 2.

Soil Physical Property	PC 1	PC 2	Factor 1	Factor 2
Bulk Density	-0.90936	0.00093	-0.89122	-0.18074
Total Porosity	0.90808	-0.12546	0.91484	0.05846
Macroporosity	0.54023	0.30407	0.46860	0.40585
Microporosity	0.83116	-0.19594	0.85355	-0.02596
Field Capacity	0.95823	-0.16541	0.97196	0.02934
0.1 MPa Moisture Content	0.85807	-0.31137	0.90297	-0.13369
Saturated Hydraulic Conductivity	0.79775	0.09157	0.76338	0.24908
Unsaturated Hydraulic Conductivity	-0.03791	0.89200	-0.21533	0.86645
Air Permeability	0.20679	0.86082	0.03066	0.88478
Soil Strength	-0.45807	-0.70255	-0.30849	-0.77989

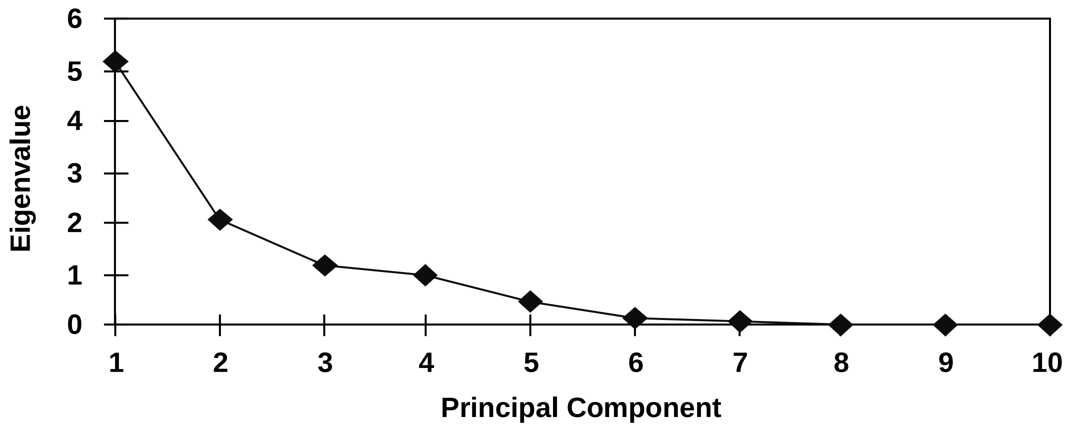
Subsurface Soil Horizon

Physical properties of subsurface soil horizons were evaluated. Principal components 1 and 2 explained 71.8% of overall data variation (Figure IV-7). Bulk density, total and microporosity, field capacity, and 0.1 MPa moisture content showed high weights in PC 1; therefore, PC 1 explained soil void characteristics. Macroporosity and saturated hydraulic conductivity had high weights in PC 2; therefore, PC 2 explained hydraulic properties. Soil strength was moderately high in PCs 1, 2, and 3. Principal component 3 included medium weights ($|\lambda| \cong 0.60$) of unsaturated hydraulic conductivity and air permeability. This might indicate a possibility of a third axis, which is a soil permeability/structure property axis, because unsaturated hydraulic conductivity and air permeability are measures of structural resistance of a soil on media. However, the eigenvalue of PC 3 was 1.17, which was relatively small compared to the eigenvalue of PCs 1 and 2 (5.15 and 2.03, respectively). Therefore, only PC 1 and PC 2 were used for further analysis. These results also indicated that soil void space, hydraulic property, and possibly permeability/structure property were important measures in evaluating subsurface soil properties.

Subsurface soil PCs 1 and 2 were rotated to maximize the variances along the axes. The orthogonal transformation matrix was very close to the identity matrix, which means that the rotation was very small and the change of each variable weight between principal component and factor was also small (Table IV-5). Orthogonal transformation matrix was:

$$T = \begin{bmatrix} 0.99990 & -0.01420 \\ 0.01420 & 0.99990 \end{bmatrix}$$

Loading of Factors 1 and 2 were used to calculate variable scores for biplot analysis.



PC	1	2	3	4	5	6	7	8	9	10
BD	-0.93191	-0.28408	-0.05398	-0.09122	-0.10155	0.04212	0.12224	0.11151	0.00997	0.00693
TotalP	0.93793	0.27840	0.03787	0.08610	0.07144	-0.03980	0.16282	0.01402	0.01825	-0.01408
MacroP	-0.07065	0.95593	0.08832	0.13131	0.05804	-0.22650	-0.00680	0.03669	-0.00289	0.00935
MicroP	0.97495	-0.13400	0.00580	0.02278	0.05273	0.05977	0.15309	-0.02192	-0.02296	0.01282
FC	0.98752	-0.04569	0.03638	0.02551	0.07518	0.08615	-0.08106	0.00567	0.02984	0.01340
MC	0.97297	-0.10740	-0.06900	0.09271	0.05576	0.03572	-0.10367	0.11398	-0.01666	-0.00611
Ksat	0.23222	0.75573	-0.38940	-0.19283	-0.40303	0.15387	-0.00301	-0.00280	-0.00138	-0.00059
Kunsat	-0.30889	0.24823	0.66038	0.60901	-0.10832	0.15566	0.00244	0.00253	-0.00186	-0.00078
Kair	-0.05317	0.33956	0.60567	-0.69267	0.16484	0.08891	-0.00356	0.01165	-0.00299	-0.00145
Strength	-0.60842	0.42540	-0.44802	0.16110	0.44139	0.16509	0.01046	-0.00047	-0.00112	-0.00058

Figure IV-7. Scree plot of principal component eigenvalues for subsurface soil physical properties and the variable weights for each principal component. Soil physical property variables are bulk density (BD), total, macro, and microporosity (TotalP, MacroP, and MicroP, respectively), field capacity (FC), 0.1 MPa soil moisture content (MC) saturated and unsaturated hydraulic conductivity (Ksat and Kunsat, respectively), air permeability (Kair), and soil strength (Strength).

Table IV-5. Subsurface soil physical property weights for principal components (PC) 1 and 2 and Factors 1 and 2.

Soil Physical Property	PC 1	PC 2	Factor 1	Factor 2
Bulk Density	-0.93191	-0.28408	-0.93585	-0.27081
Total Porosity	0.93793	0.27840	0.94179	0.26505
Macroporosity	-0.07065	0.95593	-0.05707	0.95684
Microporosity	0.97495	-0.13400	0.97295	-0.14783
Field Capacity	0.98752	-0.04569	0.98677	-0.05971
0.1 MPa Moisture Content	0.97297	-0.10740	0.97135	-0.12121
Saturated Hydraulic Conductivity	0.23222	0.75573	0.24293	0.75236
Unsaturated Hydraulic Conductivity	-0.30889	0.24823	-0.30533	0.25259
Air Permeability	-0.05317	0.33956	-0.04834	0.34028
Soil Strength	-0.60842	0.42540	-0.60232	0.43400

Biplot Analysis

Results of factor analysis were plotted on biplots for overall soil disturbance and amelioration evaluation (Figure IV-8). A biplot is a plot of variable weights and observation scores that shows relative importance and relations of variables and observations. Weights of variables and scores of observations for Factors 1 and 2 are analogous to X and Y coordinates. Evaluation of variable locations and the distances from axis origin provide an interpretation of each axis (Figures IV-8A and 8C), and characteristics of each observation or group of observations can be explained based on the axis interpretations (Figures IV-8B and 8D). In the surface horizon biplot (Figure IV-8A), total and microporosity, field capacity, 0.1 MPa moisture content, and saturated hydraulic conductivity were closely located, which indicated the high correlation among the properties, but bulk density was located opposite of those properties, showing that bulk density was negatively correlated with these properties. Those property vectors were parallel to the Factor 1 axis. This confirmed that the Factor 1 axis was a measure of 'void space.' Similarly, unsaturated hydraulic conductivity, air permeability, and soil strength vectors were parallel to the Factor 2 axis; therefore, this axis was a measure of 'soil structural resistance.' Interpretation of surface and subsurface horizon Factor 1 axes were similar because total and microporosity, field capacity, 0.1 MPa moisture content, and bulk density vectors of subsurface horizons were relatively parallel to the Factor 1 axis (Figure IV-8C). The Factor 2 axis of the subsurface horizon biplot was a measure of 'hydraulic property' because saturated and unsaturated hydraulic property and air permeability vectors were parallel to the Factor 2 axis.

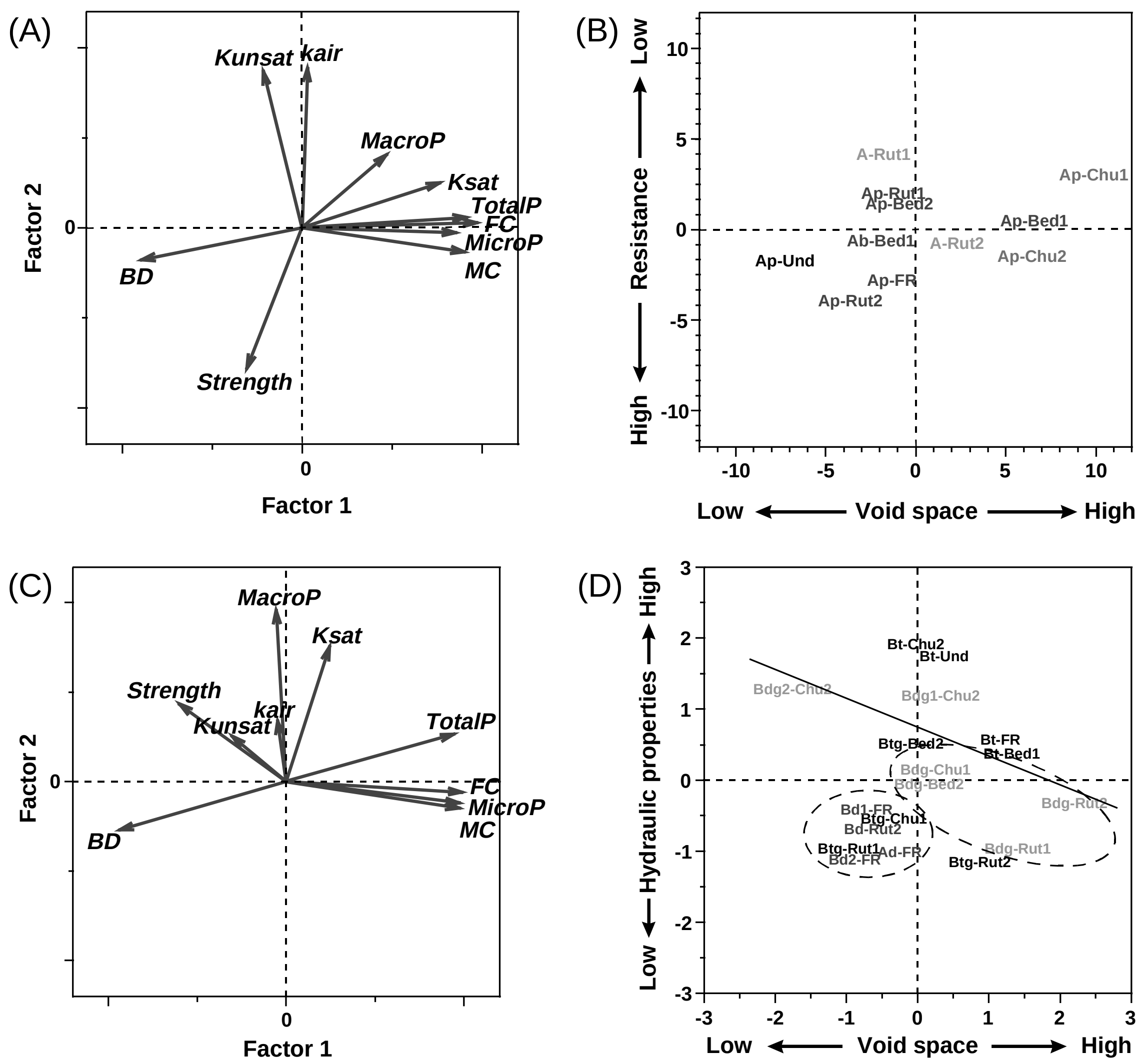


Figure IV-8. Biplot of surface soil horizon physical property variables (A) and observations (B), and subsurface soil horizon physical property variables (C) and observations (D). Variables include bulk density (BD), total, macro-, and microporosity (TotalP, MacroP, and MicroP, respectively), soil moisture content at field capacity (FC) and 0.1 MPa (MC), saturated and unsaturated hydraulic conductivity (Ksat and Kunsat, respectively), air permeability (kair), and soil strength (Strength). Observations include Ap, Ad, A, Bd, Bdg, Bt, and Btg horizons. Disturbance types include undisturbed (Und), recent deep ruts (FR), 2-yr-old deep ruts (Rut), 2-yr-old churn (Chu), and bedded soils (Bed).

Surface soil horizon biplots (Figures IV-8A and 8B) indicated that soil disturbance and bedding treatment did not have large effects on surface soil horizons. All disturbed and ameliorated surface soil horizons, especially churned surface horizons, had higher void space than the undisturbed surface horizon (Ap-Und), and many disturbed and ameliorated surface horizons had lower resistance than the undisturbed surface horizon. Although bedded surface horizons (Ap-Bed1, Ap-Bed2, and Ab-Bed) appeared to have medium resistance and medium to high void space which might be better soil attributes than some of the rutted and recently disturbed horizons (Ap-Rut2 and Ap-FR), the overall trend of surface horizons indicated that the effects of soil disturbance and amelioration on surface soil horizons were relatively small. These small soil disturbance and amelioration effects were probably caused by the incorporation of coarse organic matter in surface soils, which increased the void space and decreased resistance.

The subsurface soil biplot exhibited different characteristics between the Bd and Bdg horizons (Figures IV-8C and 8D). Since the Bd horizons (including the Ad horizon) were located close to the soil surface, these horizons received higher pressures than deeper horizons; thus, large void spaces were significantly decreased, resulting in very slow hydraulic properties (Figure IV-8D). This was indicated by the negative direction of the macropore and saturated hydraulic conductivity vectors (Figure IV-8C and Table IV-5). However, because of its shallow depth, the Bd horizon was less saturated than the Bdg and Btg horizons, as evidenced by their strong gleying (Figure IV-3).

The Bdg horizons showed relatively higher void space and slightly lower hydraulic property (Figure IV-8D). These horizons were usually located beneath the Bd horizons and had longer saturation than the Bd horizons. Therefore, the soil structure of Bdg horizons was weaker, and the weak structure was probably agitated and destroyed by vibration and pressure from the surface (Figures IV-3, 4, and 5). However, these disturbing forces slightly decreased their saturated hydraulic conductivity and macroporosity and slightly increased microporosity properties (Table IV-5). This could be explained by continuous saturation of the soil horizon. Because water occupied soil void space, the compacting force did not decrease the void space, but the force collapsed the soil structure and reduced macropores to micropores (Figure IV-8D). This was also indicated by the positive direction of the microporosity vector and the negative direction of the soil strength vector (Figure IV-8C).

Soil horizons of a churned soil (Bdg1-Chu2, Bdg2-Chu2, and Bt-Chu2) had higher hydraulic properties than the other subsurface horizons (Figure IV-8D). This might be caused by different soil type, since the sampling area consisted of different soil series than the other sampling locations.

All Bt horizons showed higher hydraulic property and void space than the other disturbed Bd, Bdg, and Btg horizons, which were separated by a line in Figure 3D. These Bt horizons had higher total and macroporosity and saturated conductivity, indicated by soil physical property vectors (Figure IV-8C). These compacted Bd and disturbed Bdg horizons probably decreased site hydrology function and higher water table.

These multivariate results indicated that soil disturbance increased surface soil porosity and decreased soil strength. Apparently the disturbance incorporated coarse organic debris. However, soil hydraulic properties, including porosity, field capacity, and saturated and unsaturated hydraulic conductivity, were decreased in the disturbed subsurface horizons, indicating that shallow subsurface water movement was altered by the disturbance.

Conclusions

Soil profiles and soil physical properties of disturbed and ameliorated soils were compared. Soil profile descriptions of surface horizons showed that large amounts of organic matter and coarse organic debris were incorporated in the horizon as a result of the disturbance. However, soil physical properties of the surface horizons (Ap) were not altered; in fact, the disturbed surface horizons had a higher void space and lower soil resistance than the undisturbed surface horizon.

A disturbed soil layer in deep ruts (Ad horizon) exposed previous subsurface soil which was severely compacted, churned, and smeared. Soil physical properties of the horizon also confirmed that the soil profile description results, especially the difference between vertical and horizontal air permeability in the recent deep ruts, indicated restricted surface water infiltration and limited lateral perched water flow through the ruts. However, this horizon was naturally ameliorated within two years of the disturbance, probably because of shrink-swell clay and biological activities. These results indicated that disturbed soil could be quickly ameliorated if the soil were exposed to frequent wet-dry cycles and aerated to enhance biological activities.

Subsurface soil horizons were significantly influenced by the surface soil disturbance. Soil profile descriptions showed that all disturbed soils consisted of compacted subsurface horizons (Bd) and/or structureless, reduced horizons (Bdg). Soil physical properties of the disturbed subsurface horizons also showed increased bulk density and stability index and decreased macroporosity, saturated hydraulic conductivity, and soil strength. These altered properties probably caused the higher water table, slower site drainage pattern, and consequent alteration of site hydrology. These results also indicated that the altered hydraulic properties remained two years after the disturbance and were not ameliorated by conventional site preparation techniques.

Bedding is a common site preparation technique used in wet pine flats to ameliorate soil disturbances. A number of studies have shown that bedding improved surface soil conditions and seedling survival in wet sites (Haines and Prichett, 1964; Derr and Mann, 1977; Pritchett, 1979; Sarigumba and Anderson, 1979; Shiver and Fortson, 1979). However, this study found that bedding had no effect on the surface soil horizon physical properties, since the disturbed surface horizons were already mixed with organic matter. Similar results were found by Gent et al. (1983). Bedding was effective in increasing surface soil depth, which was beneficial in improving soil aeration for better plant growth. Therefore, bedding is probably the best current solution for disturbed site preparation, although the long-term effect of the disturbed subsurface horizons on site hydrology and future productivity is still unknown.

Results of this study have several important implications for land managers:

1. Wet-weather harvesting disturbances alter soil hydraulic properties. These alterations may increase the period of time when soils will be saturated and cause species shifts toward wetter site competitors. These alterations may decrease the opportunities for mechanical site preparation and may increase the expense of such operations.
2. Natural and artificial amelioration techniques enhance recovery of site hydrology in the upper soil horizons but do little to ameliorate the effects in subsurface horizons. The implication of this is that shallow ruts may be readily ameliorated via site preparation, yet deeper ruts may not be as easily amended.

3. Deeper tillage (bedding) or alternative site preparation techniques may prove beneficial to site recovery. Although generalizations are sometimes erroneous, it appears as though bedding should be considered for wet sites that have received harvesting (or other) disturbances. Other techniques that might be considered include mounding or rototilling machines mounted on excavators. Mitigated wetlands associated with disturbances such as highway construction might also benefit from such treatments.