Wet-Weather Timber Harvesting and Site Preparation Effects on Coastal Plain Sites: A Review

Masato Miwa, *Forest Hydrologist, International Paper Company, 719 Southland Road, Bainbridge, GA 31717;* **W. Michael Aust,** *and* **James A. Burger,** *Department of Forestry (0324), 228 Cheatham Hall Virginia Tech, Blacksburg, VA 24061;* **Steve C. Patterson,** *Forest Soil Scientist, MeadWestvaco, Forest Science Laboratory, Box WV, 180 Westvaco Road, Summerville, SC 29483; and* **Emily A. Carter,** *Soil Scientist, USDA Forest Service, Engineering Research Unit, 520 Devall Drive, Auburn, AL 36849.*

ABSTRACT: *Increased interest in sustainable forestry has intensified the need for information on the interactions of forest soils, harvesting methods, site disturbances, and the efficacy of methods for ameliorating disturbances. On wet pine flats, such as those commonly found in the Atlantic and Gulf Coastal Plains, conditions such as frequent rainfall, low relief, and poor internal soil drainage often predispose forest soils to harvest disturbances and potential damage. Typical forest operations use heavy logging equipment, such as rubber-tired feller-bunchers and skidders. During dry soil conditions,these machines cause little soil disturbance, but under moist to saturated conditions, such operations may compact soils and interfere with normal soil drainage. Many studies have been conducted to characterize soil disturbance and site preparation effects on tree seedling survival and growth and to evaluate the amelioration effect of site preparation on disturbed soils. However, results are sometimes contradictory due to site specificity, and results have not been summarized in the context of pine plantation management. This article summarizes previous research results of the wet-weather harvesting and bedding effects on soil properties as related to loblolly pine (*Pinus taeda*) productivity for a variety of Coastal Plain region sites types. South. J. Appl. For. 28(3):137–151.*

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The majority of large wood-using facilities in the southeastern United States can feasibly maintain less than a 2-week supply of wood. Within the Coastal Plain region, wet periods commonly occur for 3–6 months of the year. The wood supply and wet season combination ensures that some degree of wet-weather harvesting will occur during most years in the Coastal Plain. Furthermore, modern forest harvesting operations use large machinery because of the efficient operability and economic feasibility. Traffic from these machines may cause localized and sometimes extensive soil disturbances such as soil compaction, shallow and deep rutting, puddling/smearing, and churning, particularly if operations are conducted during moist to saturated soil conditions (Pearson and Marsh 1935, Youngberg 1959, Hatchell et al. 1970, Moehring and Rawls 1970, Davies et al. 1973, Greacen and Sands 1980, Hillel 1982, Gent et al. 1983, 1984, Pritchett and Fisher 1987, Burger et al. 1989, Aust et al. 1993, 1995, Marshall et al. 1996). Such soil disturbances have been associated with increased bulk densities, lower organic matter levels, reduced air and water movement, and altered nutrient availability (Youngberg 1959, Moehring and Rawls 1970, Gent et al. 1983, 1984, Aust et al. 1995). Additionally, research shows that these soil disturbances can decrease seedling survival and growth of commercially important plantation species such as Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in the northwestern United States (Youngberg 1959) and loblolly pine (*Pinus taeda* L.) in the southeastern United States (Hatchell et al. 1970). These results have led to concerns about how harvest disturbances may affect long-term site productivity and to speculation about how such disturbances could be ameliorated via natural or artificial means.

A wide variety of studies have been conducted to characterize the soil disturbance and site preparation effects on

NOTE: W. Michael Aust can be reached at (540) 231-4523; Fax: (540) 231-3330; waust@vt.edu.

soil properties and on tree seedling survival and growth (May et al. 1973, Terry and Hughes 1975, McKee and Hatchell 1986, Aust et al. 1995, Kelting et al. 1999). However, these results are generally site-specific, often of limited duration, and have not been summarized in the context of pine plantation management.

The objective of this article is to briefly review and summarize research results of wet-weather harvesting and bedding effects on soil properties and site productivity. The review concentrates on describing forest soil disturbance mechanisms and providing background of forest soil disturbance and the effect on forest productivity. The review also examines the amelioration effect of site preparation on soil properties and the evidence for improved tree growth and natural soil recovery processes of intensively managed pine plantations in the southeastern United States, although less information is available for these topics. These review topics are discussed, but also presented in tabular form, to provide a succinct source of literature for land managers and researchers.

Forest Soil Disturbance Mechanisms

Mechanisms of Soil Compaction on Dry to Moist Soils

Tires on machines apply a compressive force to the soil's surface, which is a combination of normal force and shear force (Davies et al. 1973, Greacen and Sands 1980, Hillel 1982). Level of disturbance is a function of the equipment weight, driving system, traveling speed, traffic frequency, soil organic matter content, soil texture, and soil water content. Typically, the severest disturbance is produced by heavy equipment with small surface traction, such as a heavy tractor with narrow, small-diameter, high-pressure tires, making multiple passes on the same area. Wet, loamy to clayey soils with low organic matter content are conditions under which a tractor of this type would cause severe soil disturbance. This section summarizes the effects of soil compaction and disturbance processes on soil physical properties. More detailed explanations of soil compaction are provided by Soehne (1958), Harris (1971), Cohron (1971), Greacen and Sands (1980), and Hillel (1982), and severe soil disturbance is described in detail by Aust and Lea (1992).

A normal force, which is also called a static force, is a downward directional pressure that is produced by gravitational acceleration acting on a mass. The vertical stress is distributed in a soil in a vertically elongated radial direction, and the greater the force the deeper will be its effects. Therefore, decreasing the weight per unit area reduces the soil stress. Reduced weight per unit area can be achieved by decreasing loads (Soehne 1958), increasing the track-soil contact area (Reaves and Cooper 1960), and reducing tire inflation pressure (Vanden Berg and Gill 1962).

Soil shearing stress is a multidirectional force that is produced by tire lugs, wheel rotation, and vibration (Hillel 1982). The tire-soil contact face is usually not a flat plain because of tire lugs. Tire lugs apply concentrated, downward pressure directly under the flat top of the lug and less concentrated angled forces from the sides of the lugs. This produces uneven stresses on the soil (Trabbic et al. 1959, Hillel 1982). The wheel rotation causes circular movement of surface soil (Yong and Osler 1966). When a wheel moves forward, soil just in front of the wheel is pushed forward and upward. As the wheel rotates, this soil is pressed downward. Then, as the wheel moves across the soil, the compressed soil is pushed backward. Vibration produced by equipment breaks contacts between soil particles and reorganizes them into more compacted structures. This process is especially common in dry to slightly moist soils (Hillel 1982).

Soil compaction occurs when the compressive force exceeds the soil resistance force among the soil particles (Harris 1971, Greacen and Sands 1980, Hillel 1982). The ability of a soil to resist compressive forces is a function of soil texture, soil organic matter content, 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. Burger (1994) determined the trafficability hazard index for the A horizon of typical wet pine flat soils (Typic Ochraqualfs) based on the volumetric soil moisture content and showed that the maximum soil strength widely varied depending on soil water content. For instance, soils with 19% water content could withstand approximately 2,230 kPa of adjusted equipment ground pressure, but soils with 28% water content could only withstand approximately 1,115 kPa ground pressure (i.e., adjusted equipment ground pressure of a medium sized skidder (10,000 kg) with 58-cm wide tire ranges from 1,115 to 2,230 kPa).

Soil water commonly exists as a thin water film around soil particles, aggregates, and connecting structures, such as clay bridges. When soil is dry, soil compaction is caused by the collapse of larger pores, but most aggregates do not change their shape because intra-aggregate resistance forces are usually larger than those of inter-aggregate forces. As soil moisture content increases, water films gradually cover the entire soil particle, and the thickness of the water film increases (diffuse double-layer expansion). This water film weakens the soil structure and decreases frictional forces between the soil particles. Therefore, moist soil aggregates are more susceptible to deformation, and the soil is more easily compacted, especially when soil water content is between the plastic and liquid limits (Greacen and Sands 1980, Hillel 1982). Consequently, moist soil compaction reduces soil porosity and increases bulk density more than dry soil compaction.

Mechanisms of Soil Smearing (Puddling) and Churning for Moist to Wet Soils

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

Under complete or near soil saturation, soil compaction levels may actually decrease, although soil churning usually increases (Soehne 1958). When the soil water content exceeds the liquid limit, actual soil compaction decreases because the water-filled soil pores are not compressible (Aust and Lea 1992). Under this condition, traffic-induced shearing stresses reorganize soil structures. The reorganization usually causes clay-polyplate slippage, soil-particle-bound breakage, and abrades colloidal coating materials from sand grains (Koenigs 1963). Multi-directional force produced by tires on large equipment moves large soil particles and flocculates fine soil particles in excess soil water. Soil rutting, churning, and plastic mud are the result of heavy machines operating on the hydrated soils.

Localized severe soil disturbance may also alter site hydrology. Aust et al. (1993) observed localized high water tables and an alteration of site hydrology following wet-weather harvesting on a gently sloping wet pine flat forest in eastern South Carolina. They found that severe soil disturbance on primary skid trails increased bulk density and decreased macro-porosity and saturated hydraulic conductivity, which increased soil saturation in the affected areas. Additionally, the altered soil physical properties and rough soil surfaces caused by wet-weather harvesting restricted surface and subsurface water flow. This further indicates that a detailed investigation of localized severe soil disturbance is critically important to evaluate site hydrology and long-term forest productivity.

Early Observations Regarding Harvest Disturbances

Early awareness of forest soil disturbance was raised in the northwestern United States in the late 1930s when heavy equipment became commonly used for forest harvesting (Table 1). Pearson and Marsh (1935) recognized that trampling by livestock and logging operations by steam skidders and tractors on clay-textured soils under wet conditions reduced soil water and air permeability and created adverse soil conditions for ponderosa pine (*P. ponderosa* Dougl. ex Laws.) seedling root growth. Steinbrenner and Gessel (1955) compared soil physical properties of tractor roads and undisturbed areas in southwestern Washington and found that bulk density was 15% higher, macroporosity was 53% lower, and soil permeability was 93% lower in the tractor road. Lull (1959) concluded in a soil compaction review article that compaction decreased soil hydraulic properties, and the subsequent infiltration decrease increased surface runoff and erosion.

Crawler Tractor-Induced Soil Disturbance Effects on Seedling Growth

Disturbance effects of crawler tractors on forest soils and the relationship with decreased tree growth or seedling survival were described in various reports published during the three-decade period between 1950 and 1980 (Tables 1 and 2). Youngberg (1959) reported that significant increases in soil bulk density and decreases of organic matter content in the surface soil (0–30 cm) on crawler tractor roads reduced soil aeration and created a nitrogen deficiency. Although subsequent survival of Douglas-fir seedlings was not affected, seedling height growth was significantly lower within the crawler tractor trails.

Similar relationships were found in eastern pine forests. Moehring and Rawls (1970) found that wet-weather thinning operations in the Coastal Plain of Arkansas increased bulk density from 1.24 Mg m^{-3} to 1.4 Mg m^{-3} (13% increase), and Hatchell et al. (1970) found that primary skid trails and log decks in the low-lying, wet, Coastal Plain soils had significantly altered soil physical properties (increased bulk density and soil strength, and decreased infiltration rate and porosity). Furthermore, Perry (1964) found that water infiltration in 26-year-old ruts in the North Carolina Piedmont was significantly lower than that of undisturbed soils. These disturbed soil properties decreased tree height and diameter growth.

Simmons and Ezell (1983) also evaluated the effect of tractor passes on the physical properties of different soil texture classes 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 an additional 1%. Seedling survival in a sandy loam soil that was compacted by one-pass was 100%, and root growth in the soil was promoted; apparently the compaction of sandy loam soil increased soil water retention capacity. However, seedling response on a sandy loam soil that was compacted by two passes, and a loamy sand soil that was compacted by one and two passes, decreased seedling survival and root growth. These results clearly showed that soil compaction of finer textured soils by a crawler tractor during wet conditions decreased seedling survival and growth.

Rubber-Tired Skidder-Induced Soil Disturbance Effects on Seedling Survival and Growth

In the 1960s, rubber-tired skidders began replacing crawler tractors in logging operations because of their superior maneuverability, speed, and economics (Stenzel et al. 1985). This shifted the focus of soil disturbances from crawler tractors to rubber-tired skidders. Contact pressure (normal static pressure) of rubber-tired skidders is generally higher than that of crawler tractors because crawler tractors have larger soil contact areas (Greacen and Sands 1980). Therefore, rubber-tired skidders potentially create greater soil disturbances. Lockaby and Vidrine (1984) evaluated different disturbance levels of northeastern Louisiana fine loamy soils (undisturbed, primary and secondary skid trails,

Table 1. Summary of wet- and dry-weather timber harvesting effects on soil properties.

	Site location	Stand type	Soil characteristics	Effect[a]	Remarks	Reference
	General	General			Soil disturbance reduced water and air permeability.	
	Eastern Oregon and Washington	Ponderosa pine	Well-drained Basaltic origin, clayey soils; pumice origin, coarse loamy sand soils; and granites origin, loams to sandy loams		26% of the total area was disturbed by tractor logging, of which 58% was deeply disturbed. Cable and horse logging disturbed 30 and 17%, respectively, of which 2% was deeply disturbed.	Garrison and Rummell (1951)
Wet-weather tractor logging: deep soil displacement, compaction, and puddling	Cascade Mountains (southwestern Washington)	Old-growth Douglas-fir	Sedimentary shale and sandstone origin, silty clay loam; basalt origin, silty clay to clay loam; and pumice origin, clay soils		Soil property change between control and cutover site was small. Significant decrease of permeability and macroporosity and increase of bulk density in skid roads. 26% of area was disturbed by skidding.	Steinbrenner and Gessel (1955)
Tractor logging: deep disturbance	Cascade Mountains (western Oregon)	Old-growth Douglas-fir	Reddish-brown Oxisols, well-aggregated, friable clayey surface soil on basalts		On tractor road, bulk density was increased, and aeration, organic matter, and nitrogen level were decreased.	Youngberg (1959)
Rutting: in and out ruts	Piedmont (central North Carolina)	Loblolly pine plantation	Clayey B horizon, typical upland Piedmont soil		26 yr after the soil disturbance, water infiltration rate in ruts was significantly lower than out of ruts.	Perry (1964)
Wet- and dry-weather thinning by crawler tractor: puddling and smearing	Coastal Plain (southeastern Arkansas)	40-yr even-aged loblolly pine	Poorly drained silt loam loess soils with fragipan at 45–60 cm depth		Dry soils were not affected by the operation. In wet disturbed soils, surface soil bulk density in the skid trails was 13% greater than undisturbed, and macro porosity was decreased 49%.	Moehring and Rawls (1970)
Tractor and skidder logging: primary and secondary skid trails and log decks	Lower Coastal Plain (South Carolina and Virginia)	Loblolly pine	Loamy sand to sandy loam surface soil and sandy loam to clay loam subsurface soil		Total average disturbed area was about 40%. Logging disturbance, especially on log desks, increased bulk density and soil strength and decreased infiltration rate and aeration porosity.	Hatchell et al. (1970)
Wet logging by rubber-tired skidder: compaction and ruts	Upper Coastal Plain (northern Mississippi)	Pine-hardwood	Loam sand to silty clay loam soils		Wheel-rutting increased bulk density 20% and decreased macro porosity and infiltration 66% and 90%, respectively.	Dickerson (1976)
Compaction by site preparation: one and two tractor passes	Coastal Plain (eastern Texas)	Loblolly pine	Sandy loam surface soil and loam to sandy loam subsurface soil		Surface soil bulk density increased about 10% in the first tractor pass, and the second pass increased 1% additionally.	Simmons and Ezell (1983)

Table 1. (continued)

	Site location	Stand type	Soil characteristics	Effect[a]	Remarks	Reference
					Bulk density, saturated hydraulic conductivity, an aeration porosity were decreased in all disturbed surface soils. Bulk density was decreased to depth of 30 cm in skid trails.	
Moist soil logging by rubber-tired skidder: whole-tree and skid trails	Piedmont (North Carolina)	Loblolly pine plantation	Clayey, kaolinitic, thermic, Typic Hapludults		Bulk density, hydraulic conductivity, an aeration porosity were decreased in all disturbed surface soils to depth of 15 cm. Bulk density and aeration porosity were decreased to depth of 23 cm in skid trails.	Gent et al. (1984)
Logging by skidder: primary and secondary trails and logging decks	Coastal Plain (northern Louisiana)	Loblolly pine plantation	Fine loamy, siliceous, thermic Typic Paleudults		Surface soil bulk density was significantly lower in primary roads and decks than the other area. Soil strength was significantly higher in the all disturbed areas, especially on primary road and decks.	Lockaby and Vidrine (1984)
Wet-weather logging by skidder and helicopter	Lower Coastal Plain (southwestern Alabama)	70-yr tupelo-cypress swamp	Vertic fluvaquent, very wet, shrink-swell clay soils		Skidding treatment decreased saturated hydraulic conductivity and redox potential significantly. Soil resistance was no different among the treatments.	Aust et al. (1989), Aust and Lea (1992)
Wet-weather logging by skidder: disturbed and rutted	Lower Coastal Plain (South Carolina)	60-yr natural loblolly pine	Clayey, mixed, thermic Typic Paleaquult, poorly drained loamy surface soil		All measured soil physical properties were altered significantly in the disturbed area. Water table was increased in severely disturbed area.	Aust et al. (1993)
Wet-weather logging by skidder: compaction and rutting	Lower Coastal Plain wet pine flat (South Carolina)	Natural loblolly pine	Moderately well to poorly drained, coarse loamy sand to loam surface soils and fine sandy clay loam to clay subsurface soils		In the compacted and rutted soils, bulk density was significantly higher, and macro porosity and hydraulic conductivity were significantly lower than untrafficked area.	Aust et al. (1995)

[a] Harvesting effect on soil; negative (−).

and logging decks) and direct-seeded loblolly pine seedling responses to the disturbed soils (Tables 1 and 2). They found that soil bulk density was about 10–14% higher in primary skidding roads and logging decks compared to undisturbed areas, and seedling survival and height growth in the disturbed areas were 88–91% and 39–59% lower, respectively, than those of the undisturbed areas.

Rubber-tired skidders also caused severe soil disturbances such as soil smearing, rutting, and churning in wet, fine-textured soils in the Southeastern Lower Coastal Plain (Hatchell 1981, McKee and Hatchell 1986). These severe soil disturbances are commonly associated with the breakage of soil aggregates, realignment of soil particles, formation of water and air impermeable layers which often prolongs soil saturation period, decreased decomposition rate of incorporated organic matter, and decreased seedling survival and growth (Shoulders and Terry 1978). Scheerer et al. (1994) compared planted loblolly pine seedling growth within rutted and undisturbed sites in a wet pine flat in South Carolina. They found higher mortality and lower

Table 2. Summary of wet- and dry-weather timber harvesting effects on subsequent tree growth.

Type of disturbance	Site location	Stand type	Soil characteristics	Tree age[a]	Tree survival[b]	Tree growth	Remarks	Reference
		Old growth Douglas-fir	Reddish-brown Oxisols, well-aggregated, friable clayey surface soil on Miocene basalts				Seedling survival in 1st and 2nd growing seasons were same across the treatments. Seedling growth was the lowest in tractor roads and the highest in noncompacted area.	
Rutting: in and out ruts	Piedmont (central North Carolina)	Loblolly pine plantation	Clayey B horizon, typical upland Piedmont soil	26	N/A		Tree height, diameter, and volume in the ruts were less than those out of ruts.	Perry (1964)
Wet- and dry-weather thinning by crawler tractor: puddling and smearing	Coastal Plain (southeastern Arkansas)	40-yr even-aged loblolly pine	Poorly drained silt loam loess soils with fragipan at 45–60 cm depth	40	N/A		Trees which were disturbed 3 to 4 sides of rooting area decreased basal area growth.	Moehring and Rawls (1970)
Tractor and skidder logging: primary and secondary skid trails and log decks	Lower Coastal Plain (South Carolina and Virginia)	Loblolly pine	Loamy sand to sandy loam surface soil and sandy loam to clay loam subsoil	1			Stocking of naturally seeded seedlings was lower in the primary skid trails and higher in the secondary skid trails than undisturbed area. Seedling height on the skid trails was generally lower than undisturbed area.	Hatchell et al. (1970)
Compaction by site preparation: one and two tractor passes	Coastal Plain (eastern Texas)	Loblolly pine	Sandy loam to loamy sand surface soil and loam to sandy loam subsurface soil		+−	+−	One-pass compaction on sandy loam soil showed 100% survival and increased seedling root growth, but compaction on loamy sand soil decreased survival and inhibited seedling root growth.	Simmons and Ezell (1983)
Logging by skidder: primary and secondary trails and logging decks	Coastal Plain (northern Louisiana)	Loblolly pine plantation	Fine loamy, siliceous, thermic, Typic Paleudults	5			All disturbed area decreased seedling survival and height growth, especially the decrease was significant in primary roads and decks.	Lockaby and Vidrine (1984)
Wet-weather logging by skidder: compaction and rutting	Lower Coastal Plain wet pine flat (South Carolina)	Natural loblolly pine	Moderately well to poorly drained, coarse loamy sand to loam surface soils and fine sandy clay loam to clay subsurface soils	2			Seedling survival, height growth, and volume in ruts are significantly lower than non-trafficked area.	Scheerer et al. (1994), Aust et al. (1995)

[a] Tree age (years) since the establishment.
[b] Harvesting effect on tree (seedling) survival and growth; positive (+), negative (−), no (=), and not available (N/A).

seedling growth in the rutted sites regardless of site preparation, and concluded that the rutting had negative consequences for seedling survival and growth because it decreased site drainage and aeration.

These field experimental results were further supported by 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 noncapillary porosity became less than 10%, which was achieved by a 3.5 kg cm^{-2} static pressure. Mitchell et al. (1982) conducted a similar loblolly pine growth response study by analyzing the influence 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 Mg m^{-3}, and root adsorbing capacity decreased significantly when bulk density exceeded 1.4 Mg m^{-3}. These studies clearly indicated that rubber-tired skidders

Table 3. Summary of site preparation effects on tree growth for the Atlantic Coastal Plain.

Reference	State	Soil tex.[a]	Drainage class[b]	Moisture class[c]	Spp.	Tree age[d]	Treatments	Tree survival[e]	Tree growth	Remarks
Worst (1964)	GA	s-l	WD-PD	Some wet	Slash	4	Control, Burn-Scalp, Burn-Bed, and Burn-Harrow	+	+	Bedding and harrowing enhanced initial seedling growth and survival.
May et al. (1973)	GA	s-l	WD-PD	Some wet	Slash	10	Control, Burn-Scalp, Burn-Bed, and Burn-Harrow	N/A	+	Tree height and diameter were significantly higher in bedded and harrowed sites.
Sarigumba and Anderson (1979)	GA	s-l	WD-PD	Some wet	Slash	17	Control, Burn-Scalp, Burn-Bed, and Burn-Harrow	+	+	Bedding and harrowing had higher survival. Tree growth of bedding and harrowing was higher than control and scalp but no difference between bedding and harrowing.
Hatchell (1981)	SC	l/sil	PD	Wet	Loblolly	4	Burn-Spray, Windrow-Disk, and Windrow-Bed	+	+	Bedding increased tree survival and growth, but disking decreased growth slightly.
McKee and Hatchell (1986)	SC	l-sil	PD	Wet	Loblolly	12	Herbicide, Windrow-Disk, and Windrow-Bed	+	+	Bedding increased tree height, stand BA, and volume. No response to disking.
Scheerer et al. (1994)	SC	sl-scl	PD	Wet	Loblolly	2	Control, Disk, Bed, and Disk-Bed	=	+	Bedding significantly increased seedling height.
Aust et al. (1998)	SC	sl-scl	PD-VPD	Wet	Loblolly	4	Control, Disk, Bed, and Disk and Bed	+	+	Bedding improved seedling survival, height and diameter.
Terry and Hughes (1975)	NC	l-scl	SPD-VPD	Some wet	Loblolly	3	KG-Rake, and Rake-Bed	+−	+	Bedding increased survival on the wetter sites but decreased on the dryer sites. Bedding increased tree height significantly.
Gent et al. (1986)	NC	l-scl	SPD-VPD	Some wet	Loblolly	13	KG-Rake, and Rake-Bed	N/A	+	Bedding increased tree growth significantly.
Terry and Hughes (1975)	NC		PD			13	Control and Bed	N/A	+	Bedding increased tree height and volume.
Andrews (1993)	VA	s	PD	Some wet	Loblolly	23	Control, Chop-Burn, Scalp-Bed, and Ditch	+	+	Bedding improved survival. Tree height was significantly higher in bedded and ditched plots. Poorly formed bed decreased early seedling height growth.
Malac and Brightwell (1973)			MD-PD		Slash/ Loblolly	8	Control, Disk, and Disk-Bed	N/A	+	Study sites were located in SC, GA, and FL. Bedding increased tree volume.
Shiver and Fortson (1979)			WD-PD	Mostly not wet	Slash/ Loblolly	>10	Control, Clear, Bed, and Clear-Bed	=	=	498 plots were located in the lower Coastal Plain of SC, GA, and FL. Bedding did not increase SI and stand volume.
Shiver et al. (1990)			MWD-PD	Some wet	Slash	8	Control, Chop, Burn, Bed, and Herbicide	N/A	+	20 locations in the lower Coastal Plain of GA and FL were included in the study. Bedding and herbicide increased seedling growth.

[a] Soil textural classes. s = sandy, l = loam, sil = silt loam, and scl = sandy clay loam.
[b] Soil drainage class. WD = well drained, MWD = moderately well drained, PD = poorly drained, and VPD = very poorly drained.
[c] Soil moisture class during growing season.
[d] Tree age (year) since the establishment.
[e] Bedding site preparation effect on seedling survival and growth; positive (+), negative (−), no (=), and not available (N/A).

caused significant soil compaction that reduced seedling survival and growth.

Amelioration Effects of Site Preparation

Tillage as a Site Preparation Method

Forest site preparation manipulates surface soils and is intended to improve soil conditions for seedling survival and tree growth (Pritchett and Fisher 1987). Various mechanical treatments such as burning, scalping, chopping, subsoiling, harrowing, disking, bedding, mounding, and complete clearing have been used for site preparation. Advantages of site preparation are (1) decreasing or dispersing harvest debris; (2) controlling or reducing vegetative competition; (3) exposing mineral soil for better germination; (4) incorporating organic matter in surface soil to increase soil carbon storage and soil mineralization; (5) ameliorating

Table 4. Summary of site preparation effects on tree growth for the Florida Penisula.

Reference	State	Soil tex.[a]	Drainage class[b]	Moisture class[c]	Spp.	Tree age[d]	Treatments	Tree survival[e]	Tree growth	Remarks
	FL		PD							Bedding increased seedling survival and height growth significantly in old field and forested land.
Bethune (1963)	FL	s	PD		Slash	3	Control and Bed	=	+	Bedding increased seedling height significantly.
Haines and Pritchitt (1964)	FL		PD		Slash	4	Chop, Chop-Harrow, Chop-Bed, and Clear-Harrow	=	+	Clear-harrow was the highest tree growth, but bedding was the most cost efficient. Higher the site preparation intensity was the better the soil properties, root development, and tree growth were.
McMinn (1969)	FL		PD		Slash	5	Burn, Chop, Double chop, Clear, and Bed	+−	+	Mechanical site preparation might decrease survival but increased tree height. Bedding was the highest tree growth.
Lennartz and McMinn (1973)	FL	s	PD		Slash	10	Burn, Chop, Double chop, Clear, and Bed	=	+	All mechanical treatments increased tree growth between age 5–10 by controlling competing vegetation.
Mann and McGilvray (1974)	FL	s	MWD-PD	Some wet	Slash	8	Burn, Disk, Low bed, and High bed	N/A	+	High bed in wet sites and low bed in dry sites increased seedling heights.
Schultz (1976)	FL	s	PD		Slash	4	Control, Burn, Burn-Disk, and Burn Disk-Bed	+	+	Bedding improved survival. Seedling height growth increase were same in the bedding and disking.
Pritchett (1979)	FL	sl	PD	Wet	Slash	8	Burn, Burn-Disk, and Burn-Bed	+	+	Bedding increased seedling survival and tree height growth.
Wilhite and Jones (1981)	FL	s	PD	Wet	Slash	35	Non-bed and Burn-Bed	N/A	+=	Bedding had the highest average total height on age 35, but its annual growth became the lowest after age 18.
Burger and Pritchett (1988)	FL		PD	Wet	Slash	2	Burn-chop and Burn-Blade-Harrow-Bed		+	Seedling height, diameter, and volume in bedded area were significantly higher than chopped area. Bedding increased foliar N level but did not change P and K levels.

[a] Soil textural classes. s = sandy, l = loam, sil = silt loam, and scl = sandy clay loam.
[b] Soil drainage class. WD = well drained, MWD = moderately well drained, PD = poorly drained, and VPD = very poorly drained.
[c] Soil moisture class during growing season.
[d] Tree age (year) since the establishment.
[e] Bedding site preparation effect on seedling survival and growth; positive (+), negative (−), no (=), and not available (N/A).

disturbed soil to improve seedling root growth; and (6) raising seedlings above water saturated zones. Each treatment has different benefits. For instance, burning, scalping, and clearing remove organic matter and coarse debris and expose mineral soil, while chopping breaks down coarse woody debris and accelerates the decomposition process. However, none of these site treatments ameliorate disturbed surface soil. Subsoiling exposes mineral soil and ameliorates disturbed surface and subsurface soils, and harrowing and disking incorporate organic matter into surface soil and ameliorate disturbed surface soil. Bedding and mounding are the only methods that can incorporate organic matter, expose mineral soil, ameliorate disturbed surface soil, and raise the seedbed above the water table to provide aerated soil.

Bedding as an Ameliorative Practice for Wet-Weather Harvest Disturbances

During the last few decades, bedding has been recommended over other site preparation techniques for poorly drained and a severely disturbed areas as a potential ameliorative practice (Aust 1994). Since the 1970s, many studies have been conducted to evaluate the effects of bedding compared to the other common site preparation techniques in the southeastern pine flatwoods (Tables 3-6). Overall, results from the Southeastern Lower Coastal Plain indicate that bedding effectively ameliorates disturbed soil properties and improves seedling survival and growth for moderately to poorly drained silt loam or sandy soils. Improved survival and early seedling growth are attributed to increased aerated rooting volume (McKee and Shoulders 1970, 1974, Mann and McGilvray 1974, Andrews 1993), improved soil physical properties (Scheerer et al. 1994, Aust et al. 1998), better vegetation control by mechanical site preparation (Mann and Derr 1964, Derr and Mann 1970), increased available soil nutrients caused by increased mineralization rates (Burger and Pritchett 1988), and concentrating organic matter in the planting row (Terry and Hughes 1975, Schultz 1976).

Table 5. **Summary of site preparation effects on tree growth for the Gulf Coastal Plain.**

Reference	State	Soil tex.[a]	Drainage class[b]	Moisture class[c]	Spp.	Tree age[d]	Treatments	Tree survival[e]	Tree growth	Remarks
					Slash	6	Control, Disk, and Bed	N/A	+	Tree height was positively correlated with depth of redox potential and water table.
	LA	sil	MWD	Not wet	Slash/ Loblolly	5	Control, Furrow, Disk, and Bed	=	+	All mechanical treatments increased tree height and diameter growth, but survival was no different among the treatments.
Mann and Derr (1970)	LA	sil	MWD-PD	Mostly not wet	Slash/ Loblolly	8	Control, Disk, and Bed	=	+	Bedding increased tree height, but survival was no different among the treatments.
McKee and Shoulders (1974)	LA	sil	MWD-PD		Slash	8	Control, Disk, and Bed	N/A	+	Bedding increased total above ground biomass significantly, but nutrient analysis of biomass did not show any difference among the treatments.
Derr and Mann (1977)	LA	sil	MWD-PD	Some wet	Slash/ Loblolly	10	Control, Disk, and Bed	–	+	6 locations were included in the study. Unsettled beds decreased seedling survival, but bedding generally increased slash pine height growth.
Cain (1978)	LA	sil	MWD-PD	Some wet	Slash/ Loblolly	15	Control, Disk, and Bed	=	–	Bedding had slightly higher loblolly pine survival. Increased tree growth by beds diminished by age 15.
Haywood (1980)	LA	sil	MWD-PD		Slash/ Loblolly	15	Control, Disk, Bed, and Furrow	–	+	Bedding decreased survival and volume but increased height and diameter. Growth rate were no different among the treatments.
Tiarks (1983)	LA	sil	MWD	Not wet	Slash	13	Burn, Disk, and Bed	N/A	=	Bedding increased tree height and diameter growth until age 10, but tree height and diameter were no different among the treatments at age 13.
Haywood (1983)	LA	sil	MWD-PD	Mostly not wet	Slosh/ Loblolly	20	Burn, Harrow, and Bed	+	=	Bedding and harrowing improved survival and tree height at age 13. Growth rate were no different among the treatments after age 13.
Haywood (1994)	LA	sil	MWD-PD	Mostly not wet	Slosh/ Loblolly	7	Burn, Harrow, and Bed	N/A	–	Original site preparation was preserved, and the site was burned prior to planting. Tree height decreased most in the bedded sites.
Tiarks and Haywood (1996)	LA	sil	MWD-PD	Mostly not wet	Slash	10	Burn, Harrow, and Bed	N/A	–	Tree height in disking and bedding was lower than burn only.

[a] Soil textural classes. s = sandy, l = loam, sil = silt loam, and scl = sandy clay loam.
[b] Soil drainage class. WD = well drained, MWD = moderately well drained, PD = poorly drained, and VPD = very poorly drained.
[c] Soil moisture class during growing season.
[d] Tree age (year) since the establishment.
[e] Bedding site preparation effect on seedling survival and growth; positive (+), negative (−), no (=), and not available (N/A).

Terry and Hughes (1975), however, observed negative effects of bedding on seedling survival. They reported that bedding sandy dry sites, windrows, and sites with heavy root-mats caused droughty soil conditions that resulted in low seedling survival. Poorly formed and unsettled beds on clayey soils often cause large air pockets that lower seedling survival (Derr and Mann 1977).

Several studies have shown that bedding has positive effects on seedling survival and growth and early tree development, but long-term effect of bedding may not be positive. Enhanced seedling growth usually occurs on bedded and other mechanical prepared sites until age 8–13 years, but the growth rate converges after age 14, and tree diameter in control plots exceed those in the treated sites after age 15 (Cain 1978, Tiarks 1983, Haywood 1983, Allen and Campbell 1988). Furthermore, these studies showed that seedling height was actually lower in the second-rotation bedded areas (Tiarks and Haywood 1996) as compared to nonbedded treatments. Tiarks and Haywood attributed this negative effect of bedding in the second rotation to nutrient depletion during the first rotation because soil nutrient levels in the second rotation were near critical levels.

Natural Recovery of Disturbed Soils

Natural soil recovery processes are complex and gradual. Previous studies show that complete recovery of disturbed

Table 6. Summary of site preparation effects on soil properties.

Type of Disturbance	Site location	Stand type	Soil characteristics	Site prep.[a]	Effect[b]	Remarks	Reference
Logging	Coastal Plain pine flat woods (central Louisiana)	8-yr slash pine plantation		Control, Disk, and Bed		Mechanical treatments decreased organic matter content in surface soils significantly and generally decreased soil nutrients and CEC. Bedding improved surface soil aeration, but disking had no effect.	McKee and Shoulders (1974)
Logging	Coastal Plain pine flat woods (central Louisiana)	11-yr, 2nd rotation slash pine plantation	Fine-silty, siliceous, thermic Plinthaquic Paleudults or Typic Glossaqualfs, moderately well to poorly drained, low fertile soils, mostly not wet	Burn, Harrow, and Bed		Original site preparation was preserved, and the site was burned prior to planting. Soil strength was significantly high in the mechanical treatment plots, and soil nutrients were slightly low in the 2nd rotation.	Tiarks and Haywood (1996)
Logging	Atlantic Coastal Plain flat woods (northern Florida)	4-yr slash pine plantation	Aeric Haplaquods, poorly drained, fine sandy soils with spodic horizon in depth of 30–40 cm	Control, Burn, Burn-Disk, and Burn-Disk-Bed		Bedding increased available soil nutrients by mounding nutrient rich surface soil, decreased woody vegetation, and altered microclimate by exposing mineral soil.	Schultz (1976)
Logging	Coastal Plain flat woods (northwestern Florida)	8-yr slash pine plantation	Typic Paleaquult, poorly drained, acid, fine textured, thick, dark surface, savanna soils	Burn, Burn-Disk. and Burn-Bed	+	Bedding increased OM, N, CEC, and extractable nutrients.	Pritchett (1979)
Wet weather logging by skidder: compaction and rutting	Lower Coastal Plain wet pine flat (South Carolina)	2-yr loblolly pine plantation	Somewhat-poorly to very-poorly drained, coarse loamy sand to loam surface soils and fine sandy clay loam to clay subsurface soils	Control, Disk, Bed, and Disk-Bed	+	Wet weather harvesting created ruts. In trafficked area, bedding increased hydraulic conductivity and macro porosity significantly. Disking decreased hydraulic conductivity and macro porosity regardless trafficked or not.	Scheerer et al. (1994), Aust et al. (1998)
Logging	Lower Coastal Plain wet pine flat and pocosins (North Carolina)	3-yr loblolly pine plantation	Paleaquults, somewhat poorly drained, fine loamy, siliceous soils or Typic Albaquults, poorly drained, clayey, mixed soils	KG-Rake, and Rake-Bed	+	Bedding concentrated organic matter, P, K, Ca, Mg, and Mn.	Terry and Hughes (1975)

Table 6. (continued)

Type of Disturbance	Site location	Stand type	Soil characteristics	Site prep.[a]	Effect[b]	Remarks	Reference
Logging	Lower Coastal Plain pine flatwoods (northern Florida)	1- and 2-yr slash pine plantation		Control, Burn-chop, and Burn-Blad-Harrow-Bed	+−	Intensive site preparation increased N, P, and K in the soil solution, but decreased total N because of burning, organic matter removal, and high mineralization.	Burger and Pritchett (1988)
Logging	Lower Coastal Plain (southeastern Virginia)	23-yr loblolly pine plantation	Typic Ochraquults or Paleaquults, or Aeric Paleaquults, poorly drained, fine loamy, siliceous soils	Control, Chop-Burn, Scalp-Bed, and Ditch		Bedding resulted the lowest soil nutrients among the treatments because of scalping. Ditching was the highest nutrient availability because of better soil aeration and mineralization.	Andrews (1993)
Wet-weather and dry-weather logging followed by bedding	Lower Coastal Plain (South Carolina)	7-yr loblolly pine plantation	Somewhat poorly drained to very poorly drained aqualfs	Wet log and plant, dry log and plant, wet log and bed, dry log and bed		No significant difference between wet and dry logging where bedding was used. Wet harvest with no bedding had lower tree heights at age 5.	Eisenbies et al. (2004)

[a] Site preparation treatments.
[b] Site preparation effect on soil; positive (+) and negative (−).

soils can take 40 years in the North Carolina Piedmont (Perry 1964), 18 years in the Atlantic Coastal Plain (Hatchell et al. 1970), and 8–12 years in the northern Mississippi Coastal Plain (Dickerson 1976). Soil recovery process can be described with an exponential recovery curve (Webb et al. 1983). This suggests that initial recovery is fast, but a long period would be required for complete recovery. These studies suggest that soil recovery processes may vary by soil mineralogy, regional climate, and type of disturbance; however, the detailed recovery processes are not well-known.

The most important natural soil recovery process are shrinking and swelling caused by 2:1-expanding clay contents, bioturbation by soil fauna and flora, and soil expansion and contraction due to 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 populations are especially important in the Southeastern Coastal Plain because of its alluvial soil parent material, with mixed mineralogy and warm temperature climate.

Soil Recovery by Shrink-Swell Clay

Montmorillonite, a common clay mineral in soils of the Southeastern Coastal Plain, is responsible for soil shrinking and swelling (Koenigs 1963). Soil shrinkage occurs when aggregates lose inter- and intra-aggregate water. Inter-aggregate water loss causes a decrease in the double diffuse layer (the reverse process of swelling), and intra-aggregate water loss causes reorganization of the soil particles and reduction of the aggregate intra-pore space (Larson and Allmaras 1971, Brown 1977). Therefore, shrinking and swelling processes are affected by: (1) the shrink-swell clay content: (2) structural balance among soil particles (Koenigs 1963); (3) the cation concentration of the water (Bohn et al. 1985); and (4) soil water content.

Many researchers have studied soil shrink-swell behavior and the effect on soil physical properties. McGowan et al. (1983), Pillai-McGarry and Collis-George (1990), and Sarmah et al. (1996) found that disturbed soil structure improved with repeated wet-dry cycles. Pillai-McGarry and Collis-George (1990a) compared expanding and nonexpanding clayey soils under different mechanical treatments (ponded and puddled) and wetting cycles. They found that multiple wet-dry cycles produced a polygonal cracking pattern and small crumb aggregates. Repeated shrinking and swelling broke weaker soil particle bounds and caused contraction of 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. Puddling broke soil aggregates and homogenized soil structure; therefore, the strength of soil particle bounds became relatively uniform, and shrinking-swelling was less effective in producing smaller and more stable aggregates. They also found that extended dry periods did not have a significant effect on soil cracking. Miwa et al. (1999) found that deeply rutted and churned skid trails in the South Carolina Coastal Plain had partially recovered within 2 years of disturbance due to the positive effects of shrinking and swelling.

Soil Recovery by Biological Activities

Soil biological activities also contribute to soil recovery (Webb et al. 1983). Among the diverse soil organisms, earthworms, bacteria, and fungi are especially important for initial breakdown of coarse organic debris (logging slash) and litter (Gosz 1984, Waring and Schlesinger 1985, Pritchett and Fisher 1987). The primary effect of initial fragmentation of large organic debris is the physical increase of surface area and the chemical breakdown of stable soil organic matter cellular structures for further microbial decomposition (Waring and Schlesinger 1985).

Earthworms are probably the most important soil macrofauna in temperate forests because they: (1) are abundant in the forest system; (2) fragment litter and mix partially decomposed organic materials with mineral soil; (3) enhance soil structure; and (4) create continuous macropore space, which improves water permeability and soil gas exchange (Gosz 1984, Waring and Schlesinger 1985, Pritchett and Fisher 1987).

Among the diverse soil microflora, bacteria and fungi are especially important for initial breakdown of coarse organic debris and litter because of their ability to decompose plant cellulose and lignin (Waring and Schlesinger 1985, Pritchett and Fisher 1987). 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).

Although activity and abundance of fungi are a function of soil environment, fungal activity is less susceptible to changing levels of soil moisture and temperature (Baath and Soderstom 1982, Berg et al. 1998). Fungal activity is more affected by litter nutrient content and the decomposition stage. Dexter (1978) found that fungal activity decreased due to high earthworm activity because earthworms physically disrupted mycelium and predigested stable carbon for bacterial utilization.

Soil acidity has a large influence on soil biological activities (Pritchett and Fisher 1987). An acidic forest floor, such as that found in warm temperate forests, inhibits earthworm and bacteria activity (Waring and Schlesinger 1985) because an optimum soil pH for earthworm activity is between 6.0 and 8.0, and many aerobic cellulose-decomposing bacteria are active above a soil pH of 5.5. Although some earthworm species are active in acidic soils (McLean and Parkinson 1997), the primary decomposers in acidic forest floors are fungi and microfauna, such as Protozoa, Nematoda, and Enchytraeid (Gosz 1984, Waring and Schlesinger 1985), and Isopoda (Soma and Saito 1979).

The Effect of Silvicultural Practices on Soil Natural Recovery Processes

Typical site preparation techniques on Coastal Plain flats are intended to ameliorate disturbed surface soils by loosening the soils and elevating them above the water table. These elevated soils are exposed to further abiotic and biotic weathering processes. The soil recovery process is accelerated. However, disturbed subsurface soil horizons that can significantly affect site hydrology are not ameliorated by common site preparation techniques because most techniques do not aerate and loosen subsurface soils. Therefore, bedding does not improve internal soil percolation and normal water table fluctuations (Blake et al. 1976, Bullock et al.1985).

Silvicultural practices may enhance natural soil recovery processes. Because a principal natural soil recovery mechanism in the Southeastern Lower Coastal Plain is soil shrinking and swelling, a silvicultural practice that causes water table fluctuations (wet-dry cycle) would enhance the recovery process. Bedding, mole plowing (Spoor et al. 1982), subsoiling, drainage, and establishment of vegetation are examples of practices that influence the water table.

Forest operations also have significant effects on soil biological activities because the operations alter the forest soil environment. Forest harvesting typically leaves large amounts of organic debris, and the large debris is often chopped and mixed with surface soils during site preparation. Since forest harvesting increases soil surface temperature and surface water table, the post site preparation soil environment is conducive for soil biological activities.

Summary and Conclusions

Wet-weather harvesting is almost certain to occur on some sites within the Coastal Plain region due to the combination of extended periods of rainfall, low relief, and slow drainage. Wood consumers commonly attempt to minimize the impact of extended wet-weather by increasing wood inventories, but the humid conditions of the southeast, costs of wood storage, and uncertainty of the need for storage in a particular year reduce the feasibility of this option (Loving 1991, Lebel 1993). Overall, the effects of wet-weather harvesting on site productivity in the Coastal Plain are mixed because the subsequent effects are very site- and soil-dependent. Site productivity may be reduced by wet-weather harvesting on some types of sites while others are much more resistant and/or resilient to disturbance. Sites that appear to be the least susceptible to losses in long-term productivity are those that have some combination of the natural and/or artificial ameliorative properties. Important natural ameliorative properties include factors such as shrink-swell or freeze-thaw soils, natural high fertility levels, active soil fauna, and/or sediment inputs. Artificial ameliorative amendments include such common practices as mechanical site preparation, maintenance of minor drainage, or fertilization. Sites that would appear to have the greatest potential for long-term site productivity losses are those having the potential for soil erosion, little or no shrink-swell activity, and low fertility and organic matter levels. If possible, severe soil disturbances should be avoided on such sites. Over the past decade, a variety of low-impact harvesting systems and techniques, such as shovel-logging, creation of skidder corridors that use slash for reduced ground pressures, utilization of low-ground pressure forwarders and skidders, and aerial harvests, have been effectively used to minimize site disturbances on coastal plain sites (Stokes and Schilling 1997, Sloan 2001). These techniques should be considered for particularly sensitive sites or unusually wet conditions. If these sensitive sites are severely rutted and churned then artificial amelioration should be considered. Traditional site preparation practices such as bedding and fertilization have proven effective on numerous sites. In the past decade, a few land managers have implemented mounding on coastal plain sites. This technique has been widely used in the Lake States, Canada, and Scandinavia (Akerstrom and Hanell 1997), yet little data has been published regarding its efficacy on coastal plain sites. Overall, a synthesis of the research indicates that forest managers should minimize wet-weather harvesting on potentially sensitive sites, concentrate wet-weather harvesting on sites that have natural ameliorative properties, and be prepared to use additional site preparation measures as ameliorative techniques.

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