SITE DISTURBANCE AND MACHINE PERFORMANCE FROM TREE LENGTH SKIDDING WITH A RUBBER-TIRED SKIDDER

by

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(ABSTRACT)

The purpose of the study was to define the characteristics of tree-length skidding on the Lower Coastal Plain of Georgia. The objectives were: 1) to document skidder performance based on speed and tire slip, 2) to determine the effects of skidding on soil physical properties, and 3) to develop recommendations to minimize the impact on soil properties while maintaining skidder performance.

A Franklin 170 grapple skidder was operated in second gear under moist (19% moisture content) and wet (31% moisture content) soil conditions using 28L-26, 67x34-25, and 73x44-32 tires. One, three, nine, and 27 passes were tested. The skidder was also operated in third gear with the 73x44-32 tires under the wet soil condition.

With moist soil conditions skidder speed and tire slip were not affected by tire size or the number of skidder passes. Tire size did not influence soil properties. It was recommended that skidding be dispersed to avoid making more than nine passes over any particular soil area because the research indicated that repetitive passes resulted in a cumulative decrease in non-capillary porosity and an increase in bulk density.

During wet conditions, wheel slip increased, skidder speed decreased, and rut formation increased with smaller tires, an increase in the number of skidder passes, and second gear operation. Operating the skidder in third gear with the 73x44-32 tires was beneficial to skidder performance and a re-

duction in rutting. Recommendations were to disperse skidding to maintain productivity and minimize rutting.

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Introduction

The impact of mechanized forest operations on site quality has long been a major concern. The effects from the felling, skidding or yarding, and site preparation phases of intensive forest management will depend upon the condition of the site at which time the operation occurred, proper planning, and the ability to recognize conditions or practices which would deter from the best possible site quality. This research effort was focussed on the skidding phase of harvesting; in particular, articulated rubber-tired skidders.

In the southeastern United States, animals were predominantly used to skid logs up until the 1950's. Crawler tractors, along with the development of attachments and improvements, became popular because they could be used for a variety of tasks including skidding, road building, landing construction, and skid trail construction. The major drawback of the crawler tractor was its slow speed for skidding logs.

The wheeled skidder was introduced in the early 1960's and has proven to be a very efficient piece of equipment. Equipment companies have continually developed and refined the wheeled skidder to overcome some of the early problems with operability on unsuitable terrain such as lowlands and hardwood drains. The development of four-wheel drive, articulated steering, and axle oscillation, as well as the higher speeds and lower maintenance costs compared with crawler tractors, have made these machines very popular.

Within the last decade wide skidder tires have been developed to extend operations on marginally operable sites. Consequently, soil compaction and site disturbance has been reduced as the wide tires tend to distribute the load over a larger contact area, reducing contact surface pressure.

Research is necessary to define and identify the most favorable site conditions for forest operations and stand growth, while meeting economic and wood flow constraints. Results of investigations concerned with the number of skidder passes and various wide tires on site disturbance have been clouded by the complexity of situations under which skidders operate. The effect of tire size and number of passes on soil compaction and site disturbance for a given skidder is site specific, determined by soil physical properties, water drainage patterns, and vegetative cover.

This research effort was directed at defining the presence and magnitude of compaction, rutting, and disruption of subsurface drainage from articulated rubber-tired skidders under different operating and site conditions on the Lower Coastal Plain.

The objectives of the study were threefold:

1. To document skidder performance as a function of soil moisture, tire size, the number of skidder passes, and operating gear, through investigation of wheel slip and machine speed.
2. To determine the presence and magnitude of soil compaction, rutting, and disruption of subsurface drainage from articulated rubber-tired skidders under different soil moisture conditions through investigation of tire size, operating gear, and the number of passes.
3. To develop guidelines and recommendations for rubber-tired skidder operation to reduce soil compaction and site disturbance on the Lower Coastal Plain.

Literature Review

The operation of both tracked and rubber-tired skidders in harvesting operations have been recognized as one of several areas affecting site quality. Log skidding, as well as felling and site preparation, may lead to soil compaction, rutting, puddling, erosion, decreased forest productivity, and poor water quality with improper harvest planning (Conway 1976, Pritchett 1979). The extent of this disturbance from a rubber-tired log skidder may depend on many interrelated factors such as: skidder traffic intensity, size, design, and speed; tire size and inflation pressure; load; wheel slip; terrain; soil strength, moisture, and texture; and vegetative cover.

Operational Factors

Successful wood procurement requires a steady and adequate supply of wood at an acceptable cost. Harvesting operations are commonly scheduled to provide a reserve of harvestable sites throughout the year. This scheduling assures the availability of wood from "drier" sites during unforeseen wet weather conditions in which the "wetter" sites would be inoperable.

To maintain productivity and provide more flexible harvest scheduling on marginally operable sites, wide skidder tires are suggested (Porter 1983). Mellgren and Heidersdorf (1984) found the following advantages of wide tires while operating in the black spruce (*Picea mariana* (Mill) B.S.P.) swamps of northern Ontario's clay belt:

- 60% increase in production on wet ground
- Up to 40% fuel savings
- Reduction in rutting
- Reduction in soil compaction
- Smoother ride for operator comfort

The disadvantages of wide tires were found to be:

- Higher purchase cost
- Increased stress on axles and final drives
- Possible need for specialized maintenance equipment
- Restrictions on maneuverability (both harvesting and over-the-road transport due to increased vehicle width)
- Questionable performance in deep snow
- Unproven durability

As tire manufacturers introduced and improved wide tires for the logging industry, equipment companies have improved skidder design to accommodate the wide tires.

Land managers have been concerned about the potential of decreased forest productivity from site disturbance during harvesting operations. Wide tires may provide a means of reducing soil compaction and site disturbance by increasing the tire footprint area which decreases the bearing pressure at the tire/soil interface. Increasing tire width and/or tire diameter will increase the tire footprint area.

The pressure distribution under a tire depends on (1) the load, (2) the size of contact area between the tire and soil, (3) the distribution of surface pressure within the contact area, (4) tire inflation pressure, and (5) the nature of the soil. The pressure exerted on the upper soil layer is determined by inflation pressure and tire construction, while the pressure in deeper soil layers is a function of load weight (Soehne 1958).

Abeels (1976, 1982) developed the theory of soil effects and traction based on tire construction. He stated, "It is clear that the insertion of the sidewalls in the tread, and not the simple enlargement of the whole tire, is important." He argued that tire size and ply rating did not define the behavior of the tire, and supported two other parameters called the squash ratio and flattening ratio. The squash ratio is the possible variation in tire profile height from rim to tread between the unloaded and loaded condition. The flattening ratio is a variation in tire width between the unloaded and loaded condition. The squash ratio depends upon the ply rating of the tire, whereas the flattening ratio introduces sidewall rigidity. Abeels further stated that "an enlargement of the tire section in order to reduce the effects on the soil does not modify the distribution pattern if the manufacture (tire construction) is not changed." He concluded that a decrease in rim width for a given tire width will result in less soil compaction and an improvement in torque transmission.

Lysne and Burditt (1983) indicated that theoretical pressures under tracked or rubber-tired skidders excluded machine vibration or other dynamic forces which may contribute to the impact on the site. In a study by Burger et al. (1985), changes in soil bulk density or porosity between an unloaded rubber-tired skidder and an unloaded crawler tractor were not different, despite a 3.7-fold increase in mean contact pressure under the rubber-tired skidder. The authors suggested that the contact pressure beneath the track on the crawler tractor was not uniform; it may have been higher in the areas underneath the track rollers and lower in the areas between the track rollers. A particular area of soil would then be stressed by several pressures corresponding to the track rollers on one track, whereas the rubber-tired skidder would only stress a particular soil area twice, once by each pressure beneath each tire.

Taylor et al. (1980) investigated the effect of load using two different tire sizes in soil bins on subsurface soil compaction. Both tires were inflated to 16 psi (110 kPa) and operated at their rated dynamic load. The 30.5Lx32 tire with a load of 9,120 pounds (40,568 N) had consistently higher subsurface soil pressures than the smaller 18.4x38 tire with a load of 5,250 pounds (23,353 N). The soil pressures did not explain the observed soil bulk densities.

In another study in soil bins, tire slip and tire size influenced changes in soil bulk density (Koger et al. 1984b). Ten percent slip caused more soil compaction than 30% slip. An increase in tire size increased bulk density. The authors believed this may have resulted from the stiffer sidewalls on the wider tires since there was no significant difference in rut depth due to tire size. Chancellor (1977) hypothesized a reduction in surface pressure (i.e., wider low pressure tires) at constant load would decrease the rut depth/width ratio and cause more soil compaction near the surface.

McLeod et al. (1966) compared dual tires, wide tires, and conventional tires in soil bins. The dual tires and wide tires showed better tractive performance, less tire sinkage, and less soil compaction than the conventional sized tire. Burt et al. (1984) investigated tractive efficiency and net traction for three different skidder tires in soil bins. The tires tested were 18.4-34, 24.5-32, and 30.5L-32. There was little effect due to tire size on dry soil. The authors suggested operating the skidder tires at the minimum recommended inflation pressure to maximize tractive efficiency and net traction.

Dual-tired skidders had better trafficability than single-tired skidders on a swampy site in South Carolina (Koger et al. 1984a). The dual-tired skidders were able to skid loads through areas in which the single-tired skidders could not operate empty.

With an increase in tire size at constant load, Greene (1983) found significant reduction in soil compaction in the surface layer of moist soils (34% moisture content), but not for dry soils (19%

moisture content). Travel intensity (the number of machine passes) was also a significant variable contributing to soil compaction. Compaction increased rapidly up to three passes and then levelled off.

Results of experiments on agricultural soils in eastern Canada displayed a similar trend in which the increase in bulk density was sharp up to five passes, and then levelled off (Raghaven et al. 1976). Two different studies using a high-speed steel-track skidder in the western United States further supported this trend (Froehlich 1978, Sidle and Drlica 1981).

Koger et al. (1985) found the largest increase in bulk density after the first pass using a single wheel tire tester in soil bins. The results also indicated lower bulk densities with lower inflation pressures and larger tires.

Rummer and Sirois (1984), examined three tire sizes, 18.4-26, 23.1-26, and 67x34-26, on a site in central Alabama containing slopes exceeding 25%, small drainages, and wet bottoms. The 67x34-26 tires did show better trafficability and less soil disturbance, but not a decrease in soil compaction. The 67x34-26 tires also had higher productivity than the 23.1-26 tires. A direct comparison between the 18.4-26 and 67x34-26 tires was not made. The authors noted that wide tires may actually lead to more soil compaction due to the fact that load can be increased. In their study, load was not controlled and soil sample size was small.

An increase in tire width will decrease tire slip at constant load. Skidder tires can contribute to soil compaction by shearing the soil. Davies et al. (1973) found wheel slip to be more important in causing soil compaction than additional wheel loading in a study on agricultural soils. Compaction from wheel slip occurred for all tire sizes tested on a clay agricultural soil (Raghaven et al. 1978). Very high slip (greater than 50%) caused deep rutting and less compaction.

Tread depth is an important tire characteristic affecting tractive performance. Biller and Hartman (1971) found no significance of skidder tire tread depth on wheel slip for dry soil (13.6% moisture content). Maximum pull with no tread tires on the dry soil was 10,000 pounds (4536 kg). On wet soil, tread depth was very significant with maximum no tread pull and 3/4 tread pull of 2,500 pounds (1134 kg) and 4,200 pounds (1905 kg), respectively. The study was conducted on a plowed and disked area. Batardy and Abeels (1985) indicated a reduction in cleat height of 30% would decrease tractive efficiency 50%, and require higher power engines and maximum slip to obtain traction.

The shear force required to pull a load of logs significantly contributed to compaction on a forest soil in California (Miles et al. 1981). A 10 and 20% increase in soil bulk density was observed for the unloaded and loaded rubber-tired skidder mounted with 23.1-26 tires, respectively (one pass, 15cm depth, 23% soil moisture content). Chancellor (1977) indicated that high contact pressures and high shear will result in the lowest soil porosities (highest bulk densities).

Sidle and Drlica (1981) compared soil compaction from uphill and downhill skidding using a high-speed steel-track (FMC) skidder in the Oregon Coast Ranges. The mean control bulk density of the clay loam soil was 0.49 and 0.53 g/cc for the 7.5 cm and 15 cm depths, respectively. Mean increases in bulk density at the 7.5 cm depth were 42.4 and 31.4% for uphill and downhill skidding, respectively. Mean increases in bulk density at the 15 cm depth were 32.2 and 25.5% for uphill and downhill skidding, respectively. There were no significant differences between skidding direction at depths greater than 22.5 cm.

Gao (1985) examined tree-length skidding using two tire sizes, 24.5-32 and 66x43-25, on slopes of 20, 25, and 30%, in Georgia. The wide tires attained higher average travel speeds and exhibited greater sideslope stability. In 50% of the measurements, the wide tires had less wheel slip than the narrow tires.

A differential lock will also affect wheel slip. The differential lock will direct power equally to the wheels. There are three types of differential locks: mechanical, hydraulic, and automatic (no-spin). The mechanical type locks both the axle and differential housing together with a spline collar. The axle and housing are thus forced to rotate together. The hydraulic differential lock operates similarly to the mechanical, except hydraulic pressure is used to engage a clutch that locks the bevel gears within the differential. Since both axles are splined to the bevel gears, and the bevel gears are locked, the axles and differential housing rotate together. The automatic, or no-spin lock is different than the mechanical or hydraulic lock in that it is normally engaged but still allows differential action when turning. The no-spin unit does not allow the inside wheel on a turn to slow down, only the outside wheel to speed up (Deere and Co. 1979). Mellgren and Heidersdorf (1984) recommended manual differential locks be activated only when needed.

Straight line pull exceeded articulated pull at any given slip in a study by Richardson and Cooper (1970). The study was conducted using an articulated rubber-tired skidder on a natural undisturbed heavy clay soil free of vegetation, rocks, roots, or trees. For straight line pull, the skidder pulled an increasing load without steering until forward travel was stopped. The articulated test was conducted similarly, except the operator was allowed to steer left and right (often called "duck walking") to try and gain traction. Even though the authors found articulated pull to be less than straight pull, articulation does provide maneuverability advantages over straight frame vehicles. Articulation of the skidder repositions the wheels, allowing them to gain traction on roots, stumps, or other objects which would not have been possible if the wheels were oriented in a straight line direction.

Site Factors

The site factors related to disturbance potential have been grouped into two broad categories, soil and vegetation. Soil properties having an influence on the degree of site disturbance from vehicular traffic include: strength, moisture, texture, particle surface roughness, and organic matter content.

The ability of the soil to support a loaded skidder depends primarily on soil strength. Cone index, determined by a cone penetrometer, is the penetration resistance of a circular cone through soil, and has been used as a measure of soil strength (Perumpral 1983). Mulqueen et al. (1977) concluded that cone index is useful for comparing the relative strengths of soils under similar moisture content and structural condition. Supplementary measurements, such as moisture content, were recommended for soils in dissimilar conditions. Soil moisture plays a large role in soil strength. Generally, strength is high at low moisture content (Greacen and Sands 1980). As moisture content increases, the water acts as a lubricant between the soil particles allowing the soil to deform under compressive forces (Lull 1959). However, well-graded sandy soils (ie., beach sand) may have less strength when in a dry state.

The moisture content at the maximum bulk density to which a soil may be compacted using a predetermined compactive effort is generally known as the optimum moisture content or Proctor Limit and is soil specific (Figure 1). Force applied to the soil when the moisture content is above or below the Proctor level will lower the maximum attainable compactive bulk density. Weaver and Jamison (1951) concluded that the modified Proctor test may be used with some degree of reliability as a guide for compaction of agricultural soil by tractor operations. Attempts to predict the amount of compaction from harvesting machines using the standard or modified Proctor tests have had little success (Froehlich et al. 1980).

Research conducted by King (1979) on mechanically thinned pine plantations in Tennessee and Alabama resulted in no compaction on four of the six sites. The two sites in which compaction was observed had soil moisture contents greater than 18%, while the other four sites had less than 18% moisture content. The soil textures ranged from clay loam to loamy sand.

Compaction also has an effect on soil porosity. As soil is compacted, macropore space decreases, micropore space increases, and total pore space is reduced (Jakobsen 1973). In a study by Howard

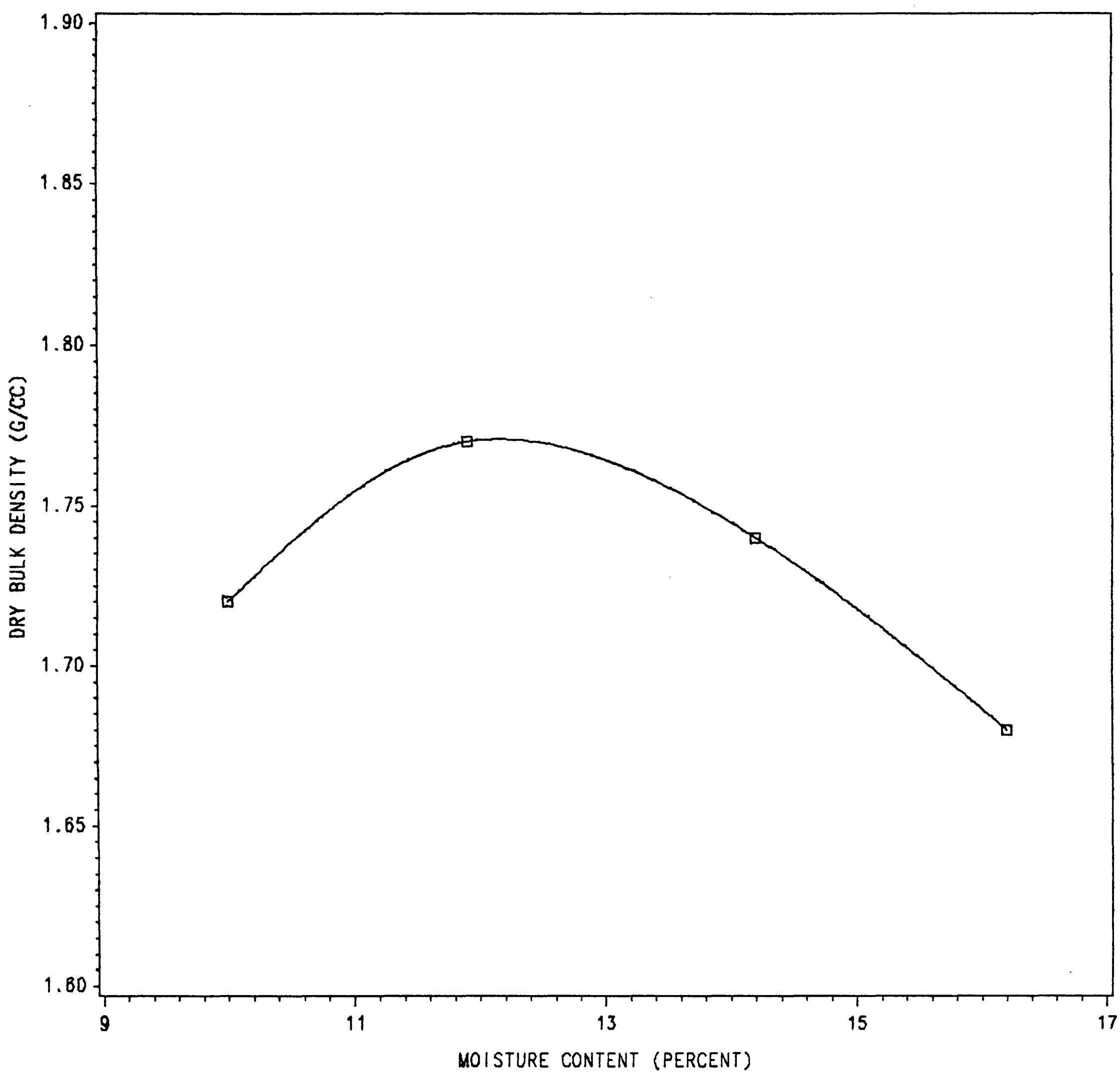

Figure 1. Proctor Curve: from Rummer and Sirois 1984.

and Singer (1981) air permeability[1] was not correlated with bulk density, but it was a significant indicator of soil disturbance.

Steinbrenner and Gessel (1955) examined the effect of a tracked log skidder on macroscopic pore space of a forest soil in southwestern Washington. The harvest area and skid roads had macroscopic pore space decreases of 10 and 53%, respectively. Boyle et al. (1982) found decreases in total porosity of 12, 32, and 16% for the 0-5, 5-10, and 10-15 cm soil depths respectively, for a Sitka spruce (*Picea sitchensis* (Bong.) Carr.) stand in Ireland harvested using a modified rubber-tired farm tractor.

Changes in air permeability mirrored the changes in soil bulk density in a study on four sites on the western slopes of the Sierra Nevada Mountains of northern California (Froehlich et al. 1980). A crawler tractor, rubber-tired skidder, and high-speed steel-track skidder all had similar effects on soil air permeability. There was little influence on total porosity of the surface soils for the four sites. In all cases, macropore space decreased and micropore space increased, with no significant influence due to machine type.

Soil particle distribution and clay mineralogy will influence soil compaction potential. Poorly-graded[2] coarse textured soils and fine textured soils with non-expanding clays will compact to similar bulk densities over various moistures. Well-graded[3] coarse textured soils and fine textured soils possessing expandable clay minerals will have compacted bulk densities dependent on soil moisture content (Froehlich and McNabb 1983). Bodman and Constantin (1965) indicated that loamy sand textures compacted to the highest bulk densities.

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[1] Air permeability is the convective transmission of air through the soil pores in response to a total pressure gradient (Hillel 1980).

[2] Poorly-graded soils are predominantly of one particle size class.

[3] Well-graded soils contain a wide range of particle sizes.

A Coastal Plain forest soil after tree-length skidding with a rubber-tired skidder had bulk densities correlated negatively with the percentages of silt (r = -0.61) and clay (r = -0.42), and positively with the percentage of sand (r = 0.61). The undisturbed soil bulk densities were not significantly correlated to any of the soil separates. Bulk density in wheel ruts increased 20%, while the bulk density of log disturbed areas increased 10%. (Dickerson 1976).

Soil particle surface roughness significantly affected the vibrational compactability of a coarse textured Coastal Plain soil in North Carolina (Cruse et al. 1980). Soil materials with the smoothest particles consistently produced the highest bulk densities at each vibrational energy level.

Compaction of soil is also a function of organic matter content. As organic matter content is increased, the maximum bulk density to which a soil may be compacted is reduced, whereas the moisture content at which maximum compaction will be attained is increased (Lowman et al. 1978, Greacen and Sands 1980).

Slash cover and litter layer have been found to dampen the compactive effect of machines on soil. Miles (1978) conducted a study on a forest site in the central Sierra Nevada Mountains to determine the compactive effect of a track-type tractor. Major skid trails had bulk density increases 40% over the undisturbed density. Minor skid trails had bulk density increases less than half of the observed increases on major skid trails. The difference in compaction on major and minor skid trails was considered to have been caused by the amount of duff material overlying the mineral soil. The number of tractor passes on major and minor skid trails was not measured.

Lack of tire-soil contact in a mechanically thinned slash pine (*Pinus elliotti* Engelm.) plantation in Alabama resulted in no detectable soil compaction (King and Haines 1979). Tree tops and branches deposited on the site from a tree harvester, and the low soil moisture content of 13% were important factors which contributed to the lack of soil compaction.

Bryan et al. (1985) assessed the importance of a slash bed on disturbance of a forest soil in New Zealand. Logs were skidded with a high-speed steel-tracked (FMC) skidder. The slash bed significantly lowered disturbance up to 60 skidder turns, at which point disturbance began increasing rapidly due to the exposed condition of the mineral soil.

Root volume within the soil may also affect the degree of disturbance from forest operations. The root systems of plants provide a support framework within the soil. The root mat in the black spruce swamps in Northern Ontario is a good example. This root mat has a much higher shear and compression strength than the underlying soil, and provides the only support for forest harvesting equipment (Mellgren and Heidersdorf 1984).

Site Disturbance Effects

Although site disturbance effects have not been well documented due to the complexities involved, there have been indications of potential decreases in site productivity and effect on water quality. Root penetration and growth may be decreased in soils which have been compacted. The high strength of compacted soils provide physical resistance to the root system. Air, water, and nutrients essential to root development may be unfavorably changed when compaction reduces soil porosity or disrupts drainage (Figure 2) (Adams and Froehlich 1981).

The reduction in soil aeration from compaction may result in anaerobic conditions. Disruption of soil drainage can also result in severe anaerobic soil conditions if the site becomes inundated for long periods. Under anaerobic conditions, nutrients may be chemically changed, making them unavailable for uptake by the root system (Cannel 1977, Pritchett 1979).

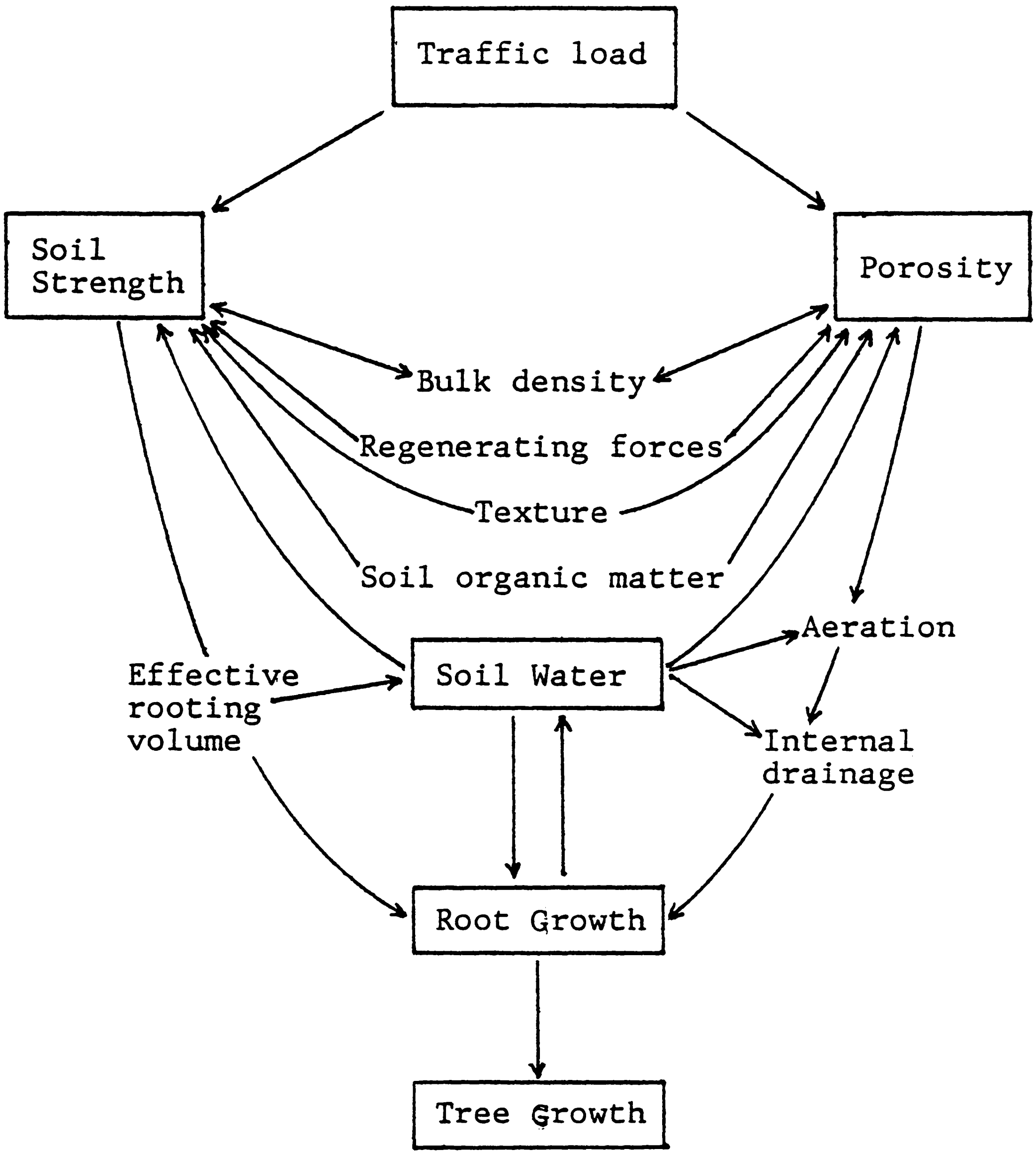


Figure 2. Interrelated factors affecting root growth: adapted from Greacen and Sands 1980.

Perry (1964) found a 46% decrease in cubic foot volume production of 26 year old loblolly pine planted in old road ruts, compared to those planted in an adjacent field. Percolation rate of one quart (0.95 liter) of water for the road ruts ranged from 80 to 240 minutes, compared to only 3.5 minutes in the field. In a study by Smith and Wass (1985) of contour skid roads and adjacent undisturbed soils in southern interior British Columbia, Canada, reduced tree growth rates were found in the gouged portions of the skid roads. The decreased rates were attributed to compaction and low organic matter and nitrogen contents. The authors recommended planting on the berm and base of skid road sidecast if both are sufficiently stable. Planting on the inside gouged portions of skid roads was not recommended due to the low predicted return on investment.

Foil and Ralston (1967) examined loblolly pine seed germination on soil cores taken from typical soils of the lower Atlantic Coastal Plain. Compaction treatments with even the smallest pressure applied (3.5 kg/cm^2) reduced aeration and increased mechanical impedance to root growth to unfavorable levels. Berben (1972) described a reduction in root growth of seedlings grown in a greenhouse with soil bulk density increases. In a study of logging damage by rubber-tired skidders on a Piedmont site in Georgia, pine seedling growth was not significantly affected one year after harvest (Campbell et al. 1973). The immediate root zone had been loosened by planting and may have reduced the compaction effects of logging for the first growing season.

Douglas-fir (*Pseudotsuga menziessii* (Mirb.) Franco) growth reductions were found on a site located in the Coast Range of Oregon which was clearcut in 1947. An 11.8% volume reduction on the site resulted from skid road and skid road-undisturbed transition zone areas (Wert and Thomas 1981). Diameter growth reduction of loblolly pine in Arkansas resulted from wet weather logging in which traffic passed on three or four sides of the tree. Dry weather logging and traffic on one or two sides of the trees did not significantly influence growth (Moehring and Rawls 1970).

Greacen and Sands (1980) indicated that wheel sinkage is generally accompanied by compaction, but in very wet saturated soil, wheel sinkage may occur with shear failure and no compaction. In such cases, soil structure is destroyed, disrupting water infiltration and increasing runoff.

Trimble and Weitzman (1953) found soil erosion was related to grade, length of slope, intensity of use, soil, vegetation, and climatic factors, in a skidding study using a crawler tractor and logging arch in the mountains of West Virginia. The typical practice at the time was to orient skid roads straight up and down the slope. Water bars and diversion ditches were recommended to reduce erosion. The Coastal Plain region of the southeastern United States is not prone to mass erosion due to the low relief, but sedimentation from the construction of roads, canals, or harvesting can affect water quality (Nutter and Gregory 1985).

Site Disturbance Amelioration

Natural amelioration of soils disturbed from harvesting equipment will depend on the extent of disturbance, soil texture and structure, freeze-thaw and wet-dry cycles, and soil organism activity level (Thorud and Frissell 1976, Adams and Froehlich 1981).

The quantity and type of clay mineral in a soil is important for shrink-swell caused by wetting and drying cycles. Soils rich in montmorillonite clay will shrink and swell with changes in moisture content (Hillel 1980). These soils are scattered throughout the southeastern United States. The shrink-swell mechanism provides an ameliorative effect to soil disturbance.

Soil freezing and thawing, as well as frost heave, can increase pore volume of the soil and is caused by the expansion property of water upon freezing. Water will expand nine percent during freezing, whereas frost heave can produce large volume changes. Approximately 90% of the soil pore space must be filled with water for frost heave to occur, given favorable soil air temperature, thermal conductivity of the soil, and litter and/or snow cover. Medium textured or compacted coarse textured soils are susceptible to frost heave (Froehlich and McNabb 1983).

Mace (1971) reported faster recovery from soil compaction in a tree-length harvested area than in a full-tree harvested area, both with rubber-tired skidders, after one overwintering period. The results were believed to have been caused by a greater degree and intensity of soil freezing due to higher soil moisture content, and lower soil compaction in the tree-length harvested area. Hatchell and Ralston (1971) predicted an 18 year average recovery of bulk density on log deck surface soils for 15 areas harvested near Franklin, Virginia. The authors assumed (1) a linear recovery of soil disturbance with time, and (2) all soils recover at the same rate throughout the recovery period. A study site in Minnesota artificially compacted using a gasoline powered tamper was predicted to recover in the top three inches of soil to pre-treatment bulk density levels between 4 and 8-3/4 years (Thorud and Frissell 1976).

Soils severely disturbed from tree-length logging with wheeled and crawler tractors on the Lower Coastal Plain of South Carolina and Virginia slowly recovered over a 19 year period (Hatchell et al. 1970). Soil bulk density recovery time for log decks was estimated to be 18 years. Primary skid trails indicated a similar recovery rate. Natural loblolly pine regeneration was retarded during the first two years on all disturbed soils.

Soil compaction from tree-length logging with rubber-tired skidders on a site in the South Carolina Coastal Plain reduced seedling growth, but did not affect survival. Seedlings planted on bedded sites, compacted or undisturbed, showed significant increases in survival and height compared to areas with no site preparation. Fertilization produced a greater seedling growth effect on compacted soil than on undisturbed soil (Hatchell 1981).

Gent et al. (1984) found that disking restored bulk densities in the 0-3 and 6-9 inch zones on a Piedmont site skid trail in North Carolina to preharvest levels. Drum chopping neither increased nor decreased bulk density after harvesting, but the authors cautioned that root growth may be restricted. Therefore, they recommended disking if future studies reveal disking compensates for the displacement of organic matter and topsoil from piling and soil erosion which occurs prior to the disking treatment. In a study on the Lower Coastal Plain of North Carolina (Gent et al. 1983), bedding was effective in restoring whole-tree and tree-length harvested plots. Bedding on skid trail plots was not as effective due to the high compacted bulk densities under the bed which may restrict root growth.

An implement developed for Douglas-fir seedbed preparation in the Northwest was found to be an efficient tool for restoring soil condition after harvest. This implement, known as the Forest Cultivator, restored bulk density to pre-harvest levels and to a maximum depth of 20 inches. It was effective on a wide range of soil types and minimized vertical mixing of the soil. This implement has not been widely tested in regions other than the Northwest (Musser 1985).

Summary

The reviewed literature presented many recommendations to reduce site disturbance from skidding, including: operate only on dry sites, operate dual tires, use wider or larger diameter tires, avoid rubber-tired skidders and use tracked machines, reduce load weight, reduce tire slip, decrease travel intensity over the same area, avoid excessive use of a differential lock, and promote systems which disperse slash over the site during harvesting.

The potential for site disturbance from rubber-tired skidders does exist, but sound solutions have not been found and applied universally, nor has the long-term impact on forest productivity been thoroughly documented. The ameliorative effect of site preparation or intrinsic site characteristics may preclude the application of several of the recommendations listed above.

Methods and Procedures

Study Area Preparation

A Lower Coastal Plain forest site in McIntosh County, Georgia was selected in October 1985. The site was soil mapped, three areas (blocks) of similar soil types located, and the boundaries marked. (Figure 3). Each block was divided into 24, 20 ft by 60 ft (6.10 m by 18.29 m) skid zones (Figure 4).

The site was harvested during the months of May and June, 1986. The area surrounding the blocks was harvested with a feller-buncher and grapple skidder. Trees within the block boundaries were chain-saw felled and cable-yarded with the skidder winch, leaving the blocks in a non-trafficked condition.

All brush was hand cut with a machete. Skid zone end stakes (3/8 in x 2 in x 5 ft, 1 cm x 5 cm x 152 cm) were installed on the outer boundaries of each skid zone. Rut stakes (2 in x 2 in x 6 ft, 5 cm x 5 cm x 183 cm) were installed 20 ft (6.10 m) from the end stakes (Figure 5).

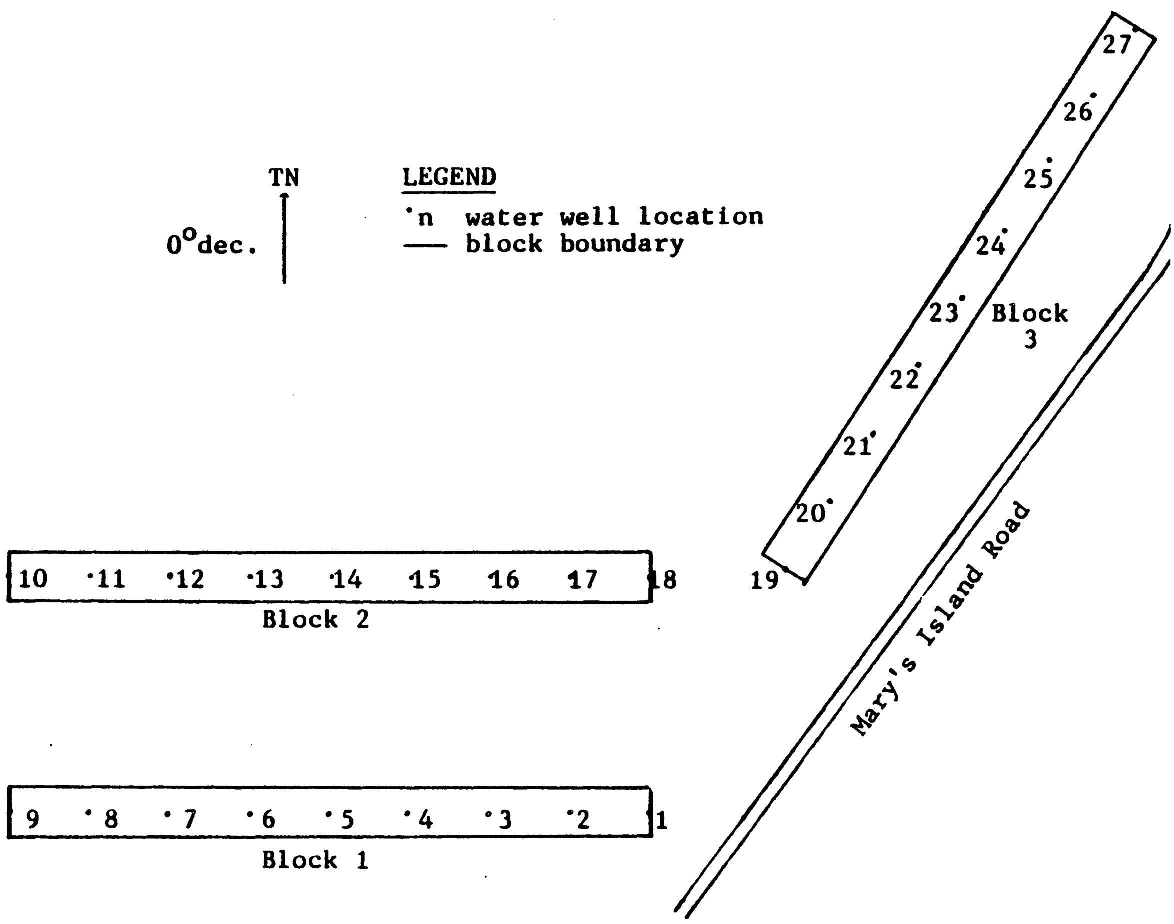
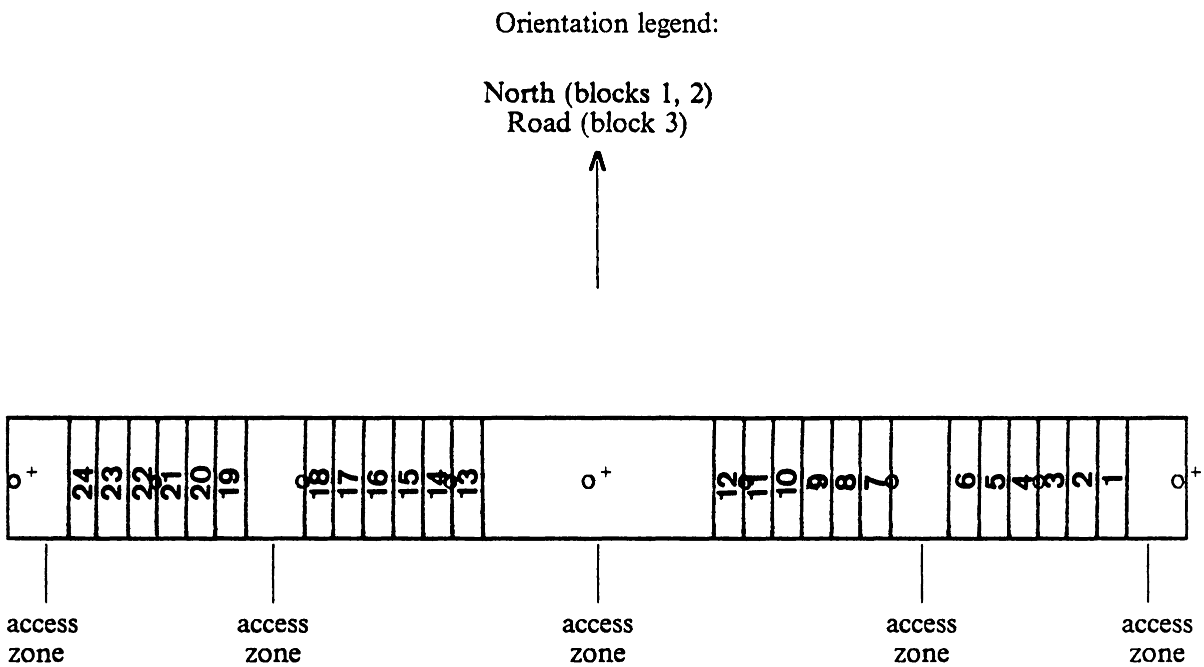
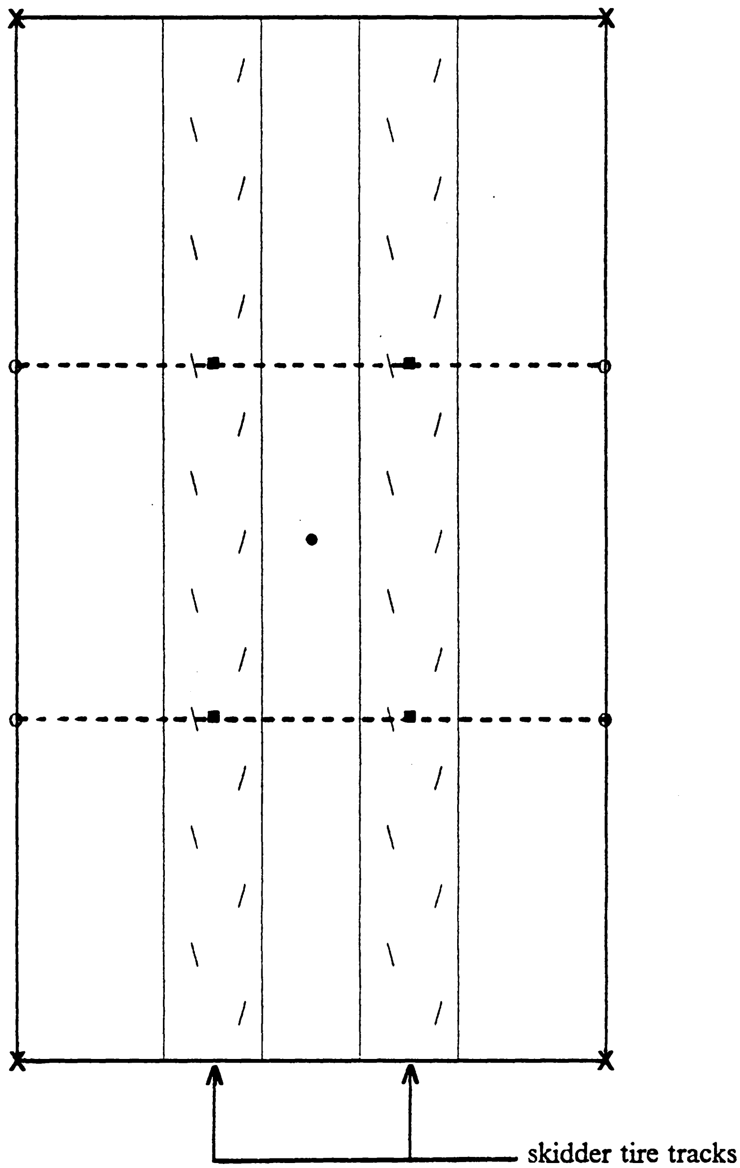


Figure 3. Study area diagram



o = pre-treatment sampling and water well location
+ = video camera location
n = zone number

Figure 4. Individual block diagram: (800 ft by 60 ft, 243.8 m by 18.3 m)



■ = sampling point (soil moisture, cone penetrometer, and treated soil core samples)

● = control soil core samples at 3 depths (0-6cm, 35-41cm, 70-76cm)

x = end stake

o = rut stake

--- = location of rut profile measurements

Figure 5. Individual skid zone diagram: (20 ft by 60 ft, 6.1 m by 18.3 m)

Experimental Design

The study was a completely randomized block design with the following treatments:

1. Soil moisture content (2 levels)
    a. moist ($\cong$20%)
    b. wet ($\cong$30%)
2. Number of skidder passes (4 levels)
    a. 1 pass
    b. 3 passes
    c. 9 passes
    d. 27 passes
3. Tire size (3 levels)
    a. 28L-26
    b. 67x34-25
    c. 73x44-32

All treatment combinations were randomly assigned to one of 24 skid zones in each block. The effect of the treatments on the following factors were analyzed.

1. Operational factors
    a. skidder speed
    b. tire slip
2. Site factors
    a. soil bulk density
    b. soil pore space
        1) total
        2) capillary

        3) non-capillary

    c. saturated hydraulic conductivity

    d. rutting

    e. cone index

The soil conditions were selected so that one level was near the optimal compactive moisture content, or Proctor Limit (moist trial), and the other was near saturation (wet trial). The optimal compactive moisture content for the soils on the study site was believed to be approximately 20-22% based on standard Proctor tests performed by Raghavan et al. (1981) on loamy sand and sandy loam soils. The near saturated soil condition was chosen to obtain maximum soil puddling and rutting effects.

The moist trial treatments were applied as planned, whereas modifications had to be made during the wet trial because the 9 and 27 pass levels could not be attained. In addition, the 28L-26 tires were inoperable at the high soil moisture content; therefore, the skid zones allocated to this treatment were reallocated to an operating strategy which involved operating the skidder in third gear with the 73x44-32 tires.

With the aforementioned modifications, analysis of variance and Duncan's multiple range test ($\alpha = 0.10$) was used on the following scenerios:

1. Moist trial
    a. Tire size (28L-26, 67x34-25, 73x44-32)
    b. Number of skidder passes (1, 3, 9 27)
2. Wet trial
    a. Tire size comparison
        1) tire size (67x34-25, 73x44-32)
        2) number of skidder passes (1, 3)
    b. Operating gear comparison

1) tire size/gear (73x44-32(2nd gear), 73x44-32(3rd gear))

2) number of skidder passes (1, 3)

c. Tire size and operating gear comparison

1) tire size/gear (67x34-25(2nd gear), 73x44-32(2nd gear), 73x44-32(3rd gear))

2) number of skidder passes (1, 3)

3. Moist vs. Wet soil conditions

a. Tire size (67x34-25, 73x44-32)

b. Number of skidder passes (1, 3)

Data Collection

Site Description

Starting at the end line of each block and thereafter every 100 ft (30.48 m), vegetative and soil information was collected prior to harvesting.

Two, 1.08 ft^2 (0.1 m^2) litter-layer samples were collected at each sampling point, oven dried at 65°C, and weighed. Basal area of the overstory was obtained with a 10 factor prism. Site index was determined using total height and total age of one dominant or codominant tree at each sample point (Newberry and Pienaar 1978). The general understory composition was also recorded.

The soil profile was described, including soil horizon designation and depth. Soil horizon samples were collected, air dried, and ground. All soil horizons from three randomly selected sampling points within each block were analyzed for texture using the hydrometer method as described by Bouyoucos (1936). Organic matter content was determined for all soil horizon samples by weight loss on ignition. The samples were oven dried at 105°C, weighed, put into a furnace at 375°C for 24 hours, and re-weighed. Organic matter was then calculated using Equation 1.

$$\% \text{ Organic Matter} = \left(\frac{\text{oven-dry weight} - \text{ignition weight}}{\text{oven-dry weight}} \right) \times 100 \qquad (1)$$

Liquid and plastic limits using the methodology described by Sowers (1965) were determined for all soil horizons from one randomly selected sampling point in each block.

A 1.5 in diameter by 5 ft (4 cm by 152 cm) section of perforated PVC pipe was installed as a water well in each auger hole from which the soil horizon samples were collected. The water table depth was measured over the course of the study. The relative elevation of the ground surface at each sampling point (water well) was determined using a tripod level. The ground surface and soil horizons for each block were plotted using the SAS/GRAPH computer package (SAS Institute, Inc. 1985).

Intact 135cc soil core samples were collected at the surface, 13.8-16.1 in (35-41 cm) depth, and 27.6-29.9 in (70-76 cm) depth in the middle of each skid zone. Oven-dried bulk density (Blake 1965), non-capillary pore space using a tension table at 50 cm of tension (Vomocil 1965), and saturated hydraulic conductivity (Klute 1965) was calculated for each soil core sample. Total pore space was calculated using Equation 2. Capillary pore space was derived by subtracting non-capillary pore space from total pore space.

$$\% \text{ Total Pore Space} = 100 - \left[\frac{\text{oven-dry bulk density}}{2.65} \times 100 \right] \qquad (2)$$

where 2.65 is an assumed particle density in g/cc (Hillel 1980).

To maintain a manageable sample size, only one soil core sample was obtained in each skid zone at each sampling depth. To provide a representative control value, the average value of each soil core sample for each group of six adjacent skid zones at each depth was used as the control sample; that is, each core sample measurement was averaged at each depth within skid zones 1 through 6, 7 through 12, 13 through 18, and 19 through 24. The skid zone groupings were chosen to reduce the variation of control values and maintain a recognition of the natural variation within the blocks by location. Values which deviated widely were tested for rejection with a Q-test (Day and Underwood 1974). If the value was rejected, the control mean was computed on the remaining five values.

Equal elevation marks were drawn on each rut stake for each group of six skid zones within each block. A steel tape was held taut across the skid zone at the levelled marks. A wooden pole marked with one inch (2.54 cm) graduations was then used to define the undisturbed topography across the skid zone at one foot (30.5 cm) intervals. This was called the control profile. There were two control profiles for each skid zone (see Figure 5). The topographic coordinates were plotted using the SAS/GRAPH computer package (SAS Institute, Inc. 1985).

Moist (July) Trial

The treatments consisted of soil moisture at time of treatment, three tire sizes (28L-26, 67x34-25, and 73x44-32), and 4 pass levels (1, 3, 9, and 27). Treatment combinations were arranged factorially in each of the three replicate blocks. Moist trial treatment combinations by block and zone are listed in Appendix B. The trial was conducted July 21-25, 1986. One Franklin 170 grapple skidder was operated with 67x34-25 tires, while another Franklin 170 grapple skidder had to be used for the 28L-26 and 73x44-32 tires due to wheel mounting restrictions on the first skidder.

The skidder was loaded with tree-length material and allowed to operate over stumps and articulate to successfully traverse the skid zones. The skidder was operated at full throttle in second gear and restricted to the same tire paths and same travel direction on multiple-pass treatments.

The skidders, when mounted with the different tire sizes, were measured for ground clearance, overall vehicle width, inside tire width, lug depth, and tire inflation pressure. A tree-length load was chosen for the study which represented a common weight and volume amount for the locale and could be skidded in ″moist″ as well as ″wet″ soil conditions. The load weight selected was approximately 6800 lb (3084 kg) and was weighed before and after each tire size treatment by suspending each tree-length stem from a log loader using a dynamometer (Figure 6). Each weight was recorded to the nearest 20 lb (9.1 kg). Load weight loss after each tire size treatment was corrected by adding a tree-length stem(s) to bring the load weight as close to the original weight as possible. The load was bound with a chain near the butts to help prevent loss during skidding.

Skidder operation through each skid zone was videotaped from stationary camera locations within each block (Figure 4). The video tape was used to determine wheel slip and skidder speed. A mark was painted on each tire and its position recorded as it passed the first end stake of each skid zone. The position of the mark was again recorded as the tire passed the first rut stake, the second rut stake, and the end stake of each zone (Figure 7). Thus, tire revolutions were obtained in each 20 ft (6.10 m) trisect of each skid zone. By the use of two video cameras, revolutions of all four tires on the skidder were recorded.

The loaded skidder was operated on a compacted haul road and the distance travelled with four tire revolutions was recorded for each of the four tires and averaged. The tire revolutions per unit distance from the video tapes was then compared to the average tire revolution per unit distance on the haul road to obtain wheel slip using Equation 3. Since the slip measurements were not based on a zero slip condition (some wheel slip, although minimal, occurred while pulling the logs on the compacted haul road), the slip values may appear lower than typically found in literature. As the slip values were based on this same condition, slip comparisons were valid. The slip values from

Figure 6. Weighing tree-length stem by suspension with a dynamometer

Figure 7. Slip measurement with video camera

this study should not be compared to values reported in other studies. The arcsine transformation of the slip data was used in the analysis of variance procedure.

$$\% \text{ Slip} = \left[1 - \frac{\text{distance skid zone / tire revolutions}}{\text{distance haul road / tire revolutions}} \right] \times 100 \qquad (3)$$

One of the video cameras was equipped with a timer to allow the determination of skidder speed. The time was recorded as the skidder passed each stake within a skid zone. Skidder speed was calculated using Equation 4.

$$\text{Speed (distance/minute)} = \frac{\text{distance}}{\frac{\text{end time - start time}}{\text{60 seconds/minute}}} \qquad (4)$$

Soil moisture samples were collected from the four sampling locations in each skid zone and composited to obtain one moisture content value per skid zone (Figure 5 on page 23). Soil moisture samples were collected before and after skidding. Cone penetrometer measurements (cone index) were taken at the same four locations every inch (2.54 cm) to a depth of six inches (15.24 cm) before and after trafficking. The cone index values were analyzed as the average of the six depth readings after skidding minus the average of the six depth readings before skidding.

Soil core samples were collected in three of the four skid zone sample locations in the tire ruts by randomly assigning a "no-sample" location. Pore space, saturated hydraulic conductivity, and bulk density were calculated for each soil core sample as previously described for the site description soil core control samples. The measurements taken on the treated soil core samples from the ruts were compared to measurements on the control soil core samples at the depth closest to which the treated soil core samples were collected.

To determine if soil moisture content had changed during the three days of the moist trial, soil moisture samples from skid zones trafficked the first day were also collected on the second and third days.

Rut profiles were measured in the same fashion as control profiles as described under the Site Description section except additional measurements were taken to provide a better graphical representation of the ruts. Rut profiles were plotted with the SAS/GRAPH computer package (SAS Institute, Inc. 1985). A digital planimeter was used to determine area of disturbance and compaction from the plotted rut profiles (see Appendix A for definitions of these variables). The square root transformation of disturbance and compaction was used in the analysis of variance procedure. The precision of the rut profile measurements was approximately ± 0.3 ft^2 (± 0.03 m^2). Precision was determined by finding the deviation of the rut and disturbance measurements during the moist trial; the values of these two measurements should have been identical (see rut profile definitions in Appendix A).

Water table depth was measured in each of the 27 water wells on the last day of the field trial.

Wet (September) Trial

The treatments for this field trial consisted of soil moisture at time of treatment, three tire size and transmission gear combinations (67x34-25(2nd gear), 73x44-32(2nd gear), 73x44-32(3rd gear)), and several pass levels which were not consistent across blocks or tire size/operating gears.

The 28L-26 tires could not be operated due to the high moisture content of the soil; the skidder could not complete one pass through the skid zone when mounted with the 28L-26 tires (Figure 8). The 67x34-25 and 73x44-32 tires were operated in second gear as was done during the moist trial. The skidder mounted with the 73x44-32 tires was also operated in third gear with a lower engine speed (lower wheel torque) in those skid zones originally designated for the 28L-26 tires. On the first pass with third gear, the operator chose a throttle position which would approximate the speed of the skidder under second gear operation with an open throttle. After the first pass, the operator tried to maintain a similar speed, but also adjusted the throttle at his discretion to reduce tire slip. For all treatment combinations involving second gear operation, the skidder was operated until the grapple had to be used to "push" the skidder from the skid zone, or until the specified number of passes was attained. For treatments which included the 73x44-32 tires while operating in third gear, the skidder was operated until it was necessary to downshift to second gear to traverse the skid zone, or until the specified number of passes was attained. Wet trial treatment combinations by block and zone are listed in Appendix B.

Since soil moisture did not change by day during the moist trial, and air temperature was not nearly as high, soil moisture calibration samples were not collected.

An additional profile measurement, called the disturbed profile, was taken in all skid zones for the wet (September) trial. A bamboo pole with one inch (2.54 cm) graduations was used to probe down through the soil which had been sheared (churn) by the tires to determine the depth of disturbance. Only one person used the bamboo probe to minimize any discrepancies in the method used to "feel" the rut bottom. Rut profiles were plotted with the SAS/GRAPH computer package (SAS Institute, Inc. 1985). A digital planimeter was used to calculate the area of disturbance, compaction, rutting, and churn (see Appendix A for definitions). The precision of the rut profile measurements was approximately ± 0.3 ft^2 (± 0.03 m^2). The square root transformation of the rut variables was used in the analysis of variance procedure.

Water table depth was measured in each of the 27 water wells.

Figure 8. Skidder mounted with the 28L-26 tires (wet trial): stuck on first pass

Results and Discussion

Site Description

The study area was a 29-yr-old slash pine (*Pinus elliottii* Engelm.) plantation that had a site index of 66 ft (20 m) at age 25 and a basal area of 118 ft^2/ac (27.2 m^2/ha). The understory vegetation consisted of a 45% cover of gallberry (*Ilex glabra* (L.) A. Gray), 41% wiregrass (*Aristida stricta* Michaux.), and 14% other species (*Acer spp.*, *Serenoa repens* (Batr.) Small, and unidentified species). The litter layer averaged 21298 lb/ac (23871 kg/ha) on a dry weight basis (Appendix C).

The soils on the study area included Bladen (clayey, mixed, thermic, Typic Albaquults), Pooler (clayey, mixed, thermic, Typic Ochraquults), and Riceboro (clayey, mixed, thermic, Arenic Paleaquults) series. These soils were characterized by a shallow water table during part of the year, an argillic horizon, and flat topography. The soil textures were loamy sand and sandy loam in the upper horizons (A through BE), and sandy clay and sandy clay loam in the Bt and BC horizons (Table 1). Organic matter content was highest in the A horizon with a mean of 2.26% (Table 2).

The liquid limits ranged from 14.5 to 28.8% (Table 3). The A and E horizons were non-plastic while the Bt and BC horizons had mean plastic limits of 16.8 and 19.2%, respectively. The cross-sectional surface topography and soil horizon profiles for each block are presented in Figure 9, Figure 10, and Figure 11.

All physical soil properties characterized for this study were related to soil texture, and exhibited changes by depth (Table 4). The relatively high bulk density values were primarily a result of the high sand content of the soils. Error due to compaction by the core sampler may have contributed to several of the extreme values, especially for the 70-76 cm depth. Extraction of soil cores at this depth was very difficult due to the adhesive characteristic of the clays. To overcome this problem, the inside of each brass cylinder was coated with a lubricant. Crayfish excavations were also a major cause of variability in the bulk density values. Several samples were found to be hollow after oven-drying and removal from the brass cylinders.

Bulk density averaged 1.26 g/cc for the surface, and 1.59 g/cc for the 35-41 cm and 70-76 cm depths. Soil organism activity in the upper soil may have provided a loosening and mixing effect which contributed to the lower bulk densities at the surface. It was noted during soil core collection that organisms such as roots, worms, grubs, and crayfish were more abundant at the surface than at greater depths. The higher organic matter content of the surface soil also contributed to the lower bulk densities at the surface (Table 2). Total pore space was calculated from bulk density (Equation 2) and therefore exhibited an inverse relationship by depth; bulk density increased with depth whereas total pore space decreased with depth.

Capillary pore space at the 0-6 cm and 70-76 cm depths were similar. The 35-41 cm depth had a mean capillary pore space more than 4% less than the 0-6 cm and 70-76 cm soil samples. The lower capillary porosity of the 35-41 cm samples resulted from the lack of fine particles in that zone due to leaching. At the 70-76 cm depth the abundance of clay particles provided the highest proportion of capillary pores to total pore space. Capillary pores made up 92% of the total pore space

Table 1. Soil textures by horizon

Horizon[1]	Soil Separates		Textural classification
	class	mean (%)	
A[2]	Sand Silt Clay	81 14 5	loamy sand
AE[3]	Sand Silt Clay	82 11 7	loamy sand
AB[4]	Sand Silt Clay	76 14 10	sandy loam
E[2]	Sand Silt Clay	77 13 10	sandy loam
EB[3]	Sand Silt Clay	70 12 18	sandy loam
BE[4]	Sand Silt Clay	68 13 19	sandy loam
Bt[2]	Sand Silt Clay	58 7 35	sandy clay/sandy clay loam
BC[4]	Sand Silt Clay	66 8 26	sandy clay loam

[1] Three sampling points were randomly selected within each block.
[2] based on 9 observations
[3] based on 2 observations
[4] based on 1 observation

Table 2. Organic matter content by soil horizon

Horizon[1]	n	Organic Matter (%) mean	standard error	minimum	maximum
A	26	2.26	0.17	1.06	4.29
AE	5	0.98	0.07	0.72	1.12
AB	1	1.99			
E	26	0.76	0.05	0.29	1.50
EB	7	1.09	0.15	0.78	1.82
BE	1	1.20			
Bt	26	1.67	0.08	0.86	2.31
BC	4	0.94	0.09	0.67	1.09

[1] All horizons sampled at each sampling point within each block (see Figure 3 on page 21).

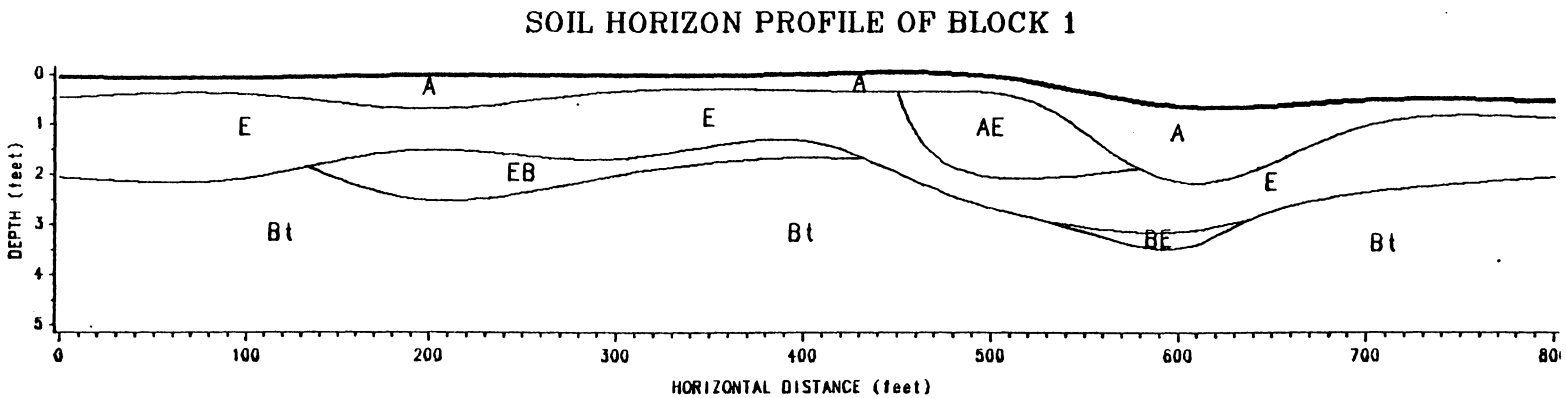
Table 3. Atterburg limits by block and horizon

Block	Location[1]	Horizon	Liquid Limit[2] (%)	Plastic Limit[3] (%)
1	8	A	16.0	non-plastic
		E	14.5	non-plastic
		Bt	28.8	17.5
2	15	A	17.7	non-plastic
		E	16.3	non-plastic
		Bt	24.6	16.9
		BC	20.2	19.2
3	24	A	16.2	non-plastic
		E	16.3	non-plastic
		Bt	26.0	16.1

[1] Refer to Figure 3 on page 21

[2] Liquid limit is the minimum moisture content at which a small sample of soil will barely flow under a standard applied force (Foth 1978).

[3] Plastic limit is the moisture content when the soil changes from a friable to a plastic consistence. It represents the minimum moisture content at which puddling will occur (Love et al. 1977).



A: sandy loam, 2.3% organic matter
AE: sandy loam, 1.1% organic matter
E: sandy loam, 0.9% organic matter
EB: sandy loam, 0.9% organic matter
BE: sandy loam, 1.2% organic matter
Bt: sandy clay/sandy clay loam, 1.8% organic matter

Figure 9. Soil horizon profile of block 1

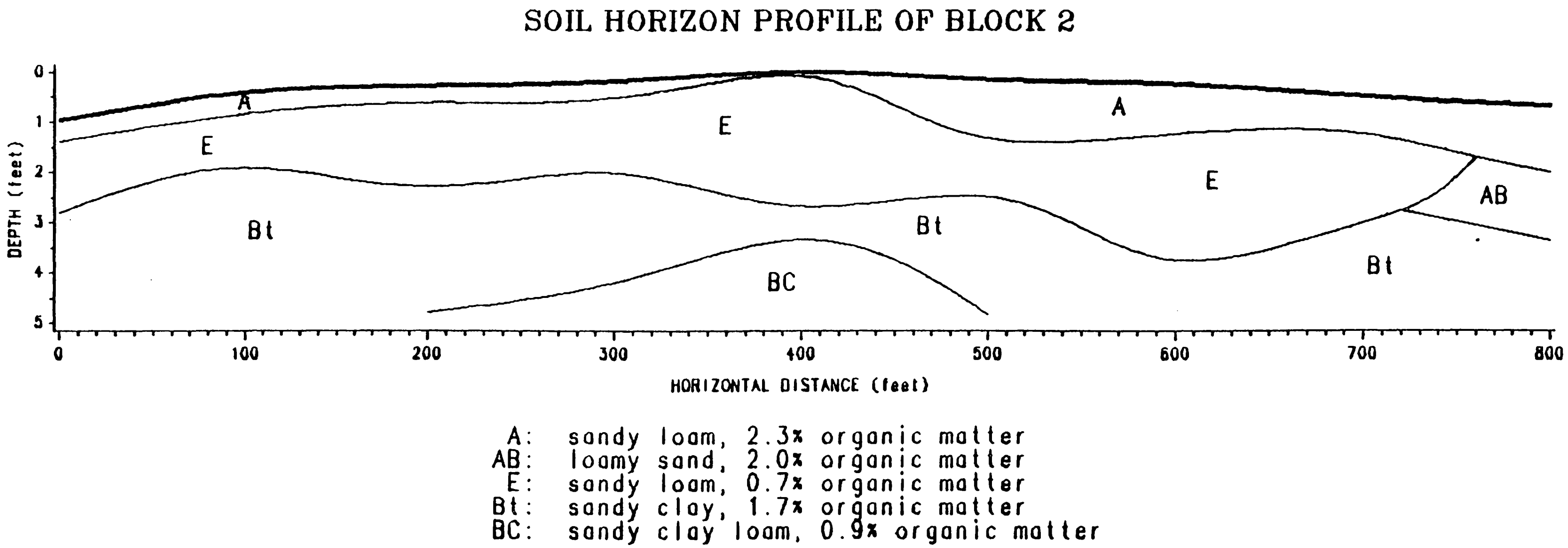
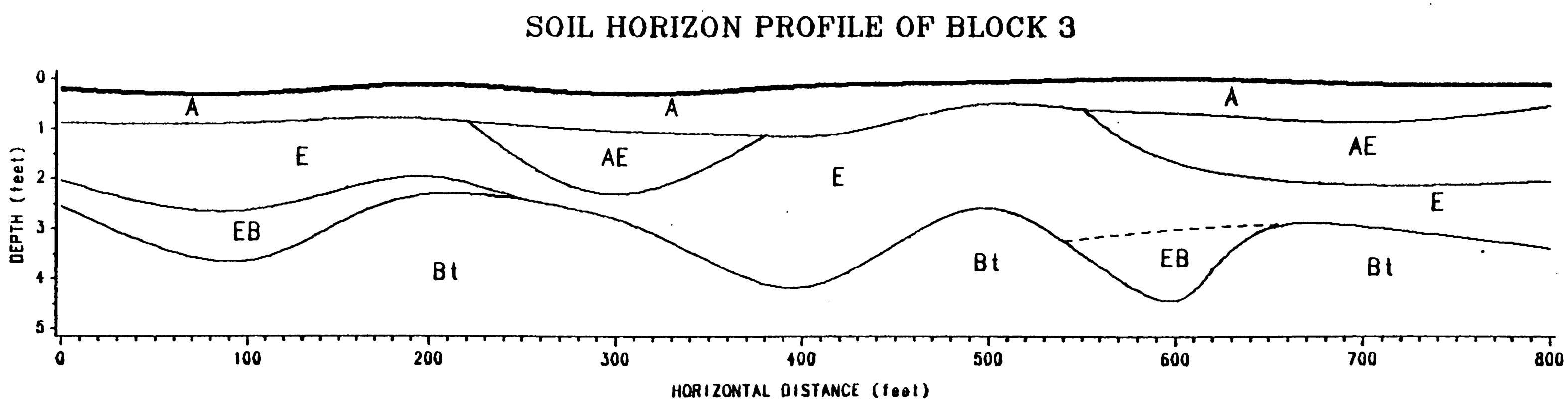


Figure 10. Soil horizon profile of block 2



A: loamy sand, 2.1% organic matter
AE: loamy sand, 1.0% organic matter
E: sandy loam, 0.6% organic matter
EB: sandy loam, 1.2% organic matter
Bt: sandy clay loam, 1.5% organic matter

Figure 11. Soil horizon profile of block 3

Table 4. Pre-treatment soil characteristics by depth

Soil Property	Depth (cm)	mean[1]	standard error	minimum	maximum
Bulk density (g/cc)	0-6 35-41 70-76	1.26 1.59 1.59	0.02 0.01 0.02	0.60[2] 1.44 1.07	1.44 1.75 1.91
Total pore space (%)	0-6 35-41 70-76	52.27 40.07 40.01	0.57 0.29 0.74	45.49 33.84 27.86	77.28[2] 45.61 59.47
Capillary pore space (%)	0-6 35-41 70-76	37.08 32.33 36.72	0.37 0.31 0.74	29.93 26.75 26.05	45.21 40.56 49.47
Non-capillary pore space (%)	0-6 35-41 70-76	15.19 7.69 3.30	0.61 0.36 0.34	6.91 2.43 0.07	34.43[2] 14.82 14.18
Saturated hydraulic conductivity (cm/hour)	0-6 35-41 70-76	64.17 2.22 0.24	10.27 1.22 0.17	1.75 0.03 0.00	453.10 88.62 12.44

[1]Mean based on 72 observations (24 skid zones x 3 blocks)
[2]This soil core sample was hollow in the middle

in the 70-76 cm zone, while the 0-6 cm and 35-41 cm zones only had 71 and 81% capillary to total pore space, respectively.

Non-capillary porosity decreased with depth, with means from 15.2% in the 0-6 cm zone, to 7.7% in the 35-41 cm zone, and 3.3% in the 70-76 cm zone. The increase in clay content decreased non-capillary porosity in the 70-76 cm zone (Foth 1978).

Saturated hydraulic conductivity depends on the size of the conducting pores in the soil, with a greater percentage of non-capillary pores resulting in higher conductivities (Hillel 1980). As can be seen in Table 4, conductivity decreased with a decrease in non-capillary pore space. There was also tremendous variation in saturated hydraulic conductivity within each sampling depth.

Moist (July) Trial

General Description

Pre-treatment soil moisture content ranged from 10.9 to 26.7%, with an average of 19.2%. Even though all treatments were randomly assigned, soil moisture content was higher within the skid zones which received the 67x34-25 tire treatment. The mean moisture content of the skid zones for the 67x34-25 tires was 21.3%, compared to 18.1 and 17.8% for the 28L-26 and 73x44-32 tire skid zones, respectively. Soil moisture content within skid zones for the four pass treatment levels was not different.

Minimum depth to water was 16.5 in (42cm), with 78% of the wells possessing water depths greater than 39.4 in (100cm) from the soil surface. Daytime temperatures exceeded 100°F (38°C) and no rainfall occurred while conducting the study.

Tree-length load weights averaged 6493 pounds (2945 kg) for the 28L-26 tires, 6328 pounds (2870 kg) for the 67x34-25 tires, and 6880 pounds (3121 kg) for the 73x44-32 tires. Load weights varied several hundred pounds, but not enough to cause differences in machine performance.

Dependent Variables

Skidder Speed

There was an interaction between tire size and number of passes for skidder speed; that is, skidder speed at a given number of passes was affected by tire size (Table 5). Mean speed was highest for the 67x34-25 tires at all pass levels, ranging from 427 ft/min (130.1 m/min) at pass 1 to 389 ft/min (118.6 m/min) at pass 27. Since these tires were operated on a different skidder than the 28L-26 and 73x44-32 tires, the higher speeds were the result of differences in governed engine RPM and axle differential gear ratios (see Appendix F).

The speeds for the skidder equipped with the 67x34-25 tires were adjusted under the assumption that the torque converter on both skidders acted as a direct drive; that is, internal slippage within the torque converter was assumed to be zero. The number of output axle shaft RPM's at the governed engine RPM's were 348.60 and 292.40 for the skidders equipped with the 67x34-25 tires and 28L-26 and 73x44-32 tires, respectively. Therefore, the output axle shaft on the skidder with the 67x34-25 tires was approximately 1.19 times faster (348.60 / 292.40 = 1.19).

Following this adjustment, mean speed for the skidder with the 67x34-25 tires was similar to the speed with the 28L-26 tires at all pass levels (Table 6). The speed by pass behavior of the 73x44-32 tires did not resemble that of the 28L-26 and 67x34-25 tires, and was difficult to explain.

Table 5. Mean skidder speed by tire size and pass, actual (moist trial)

Pass	Mean[1] [2] speed (ft/min)		
	Tire size		
	28L-26	67x34-25	73x44-32
1	352 (cde)	427 (a)	335 (e)
3	335 (e)	408 (ab)	381 (acd)
9	336 (e)	404 (ab)	404 (ab)
27	342[3] (de)	389 (abc)	317[3] (e)

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).
[3] based on 2 observations.

Table 6. Mean adjusted skidder speed by tire size and pass (moist trial)

	Mean[1] [2] speed (ft/min)		
	Tire size		
Pass	28L-26	67x34-25[3]	73x44-32
1	352 (bcd)	358 (bc)	335 (cd)
3	335 (cd)	342 (cd)	381 (ab)
9	336 (cd)	339 (cd)	404 (a)
27	342[4] (cd)	326 (cd)	317[4] (d)

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).
[3] Adjusted for governed engine RPM and axle differential ratio.
[4] based on 2 observations.

The differences in speed for the study were considered negligible due to the short distance (60 ft, 18.3 m) over which speed was measured; the differences in time to traverse 60 ft (18.3m) between the fastest (427 ft/min, 130.1 m/min) and the slowest (317 ft/min, 96.6 m/min) actual speed was less than 3 seconds. From a productivity standpoint, the differences in speed would have little importance as other factors, such as delays at the landing, would be more limiting.

Tire Slip

Tire size and number of passes had a significant affect on tire slip; however, the differences were minor (Table 7). Percent slip for the 28L-26, 67x34-25, and 73x44-32 tires was 1.5, 3.8, and -1.1, respectively (Figure 12). The negative slip value for the 73x44-32 tires was due to measurement precision, and was equivalent to no slip. The higher slip which occurred with the 67x34-25 tires may have resulted from their worn condition; the 67x34-25 tires had rounded cleats, whereas the 28L-26 and 73x44-32 tires had been used very little. As indicated by Batardy and Abeels (1985), a reduction in cleat height of 30% would reduce tractive efficiency 50%, and require higher power engines and higher slip for the traction.

Tire slip increased with the number of passes (Figure 13). The negative slip value at pass 1 was due to measurement precision. Slip at 27 passes was 3.4%, which was higher than the slip at passes 1 and 3, but not at pass 9. This increase in slip with pass was expected; with successive passes the surface soil is reworked, losing its cohesive ability. The decreased cohesive ability at a constant wheel torque will result in increased wheel slip (Batardy and Abeels 1985). With moist conditions the soil did not shear readily, and allowed the skidder to easily operate up to 27 passes with no adverse affect on performance.

Table 7. Mean tire slip by tire size and pass (moist trial)

Pass	Mean[1] tire slip (%)			Mean[2] across tire
	Tire size			
	28L-26	67x34-25	73x44-32	
1	0.5	1.0	-2.3	-0.3 (C)
3	0.5	2.0	-0.7	0.6 (BC)
9	3.3	6.0	-1.8	2.5 (AB)
27	1.5[3]	6.2	1.1[3]	3.4 (A)
Mean[2] across pass	1.5 (a)	3.8 (b)	-1.1 (c)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).
[3] based on 2 observations.

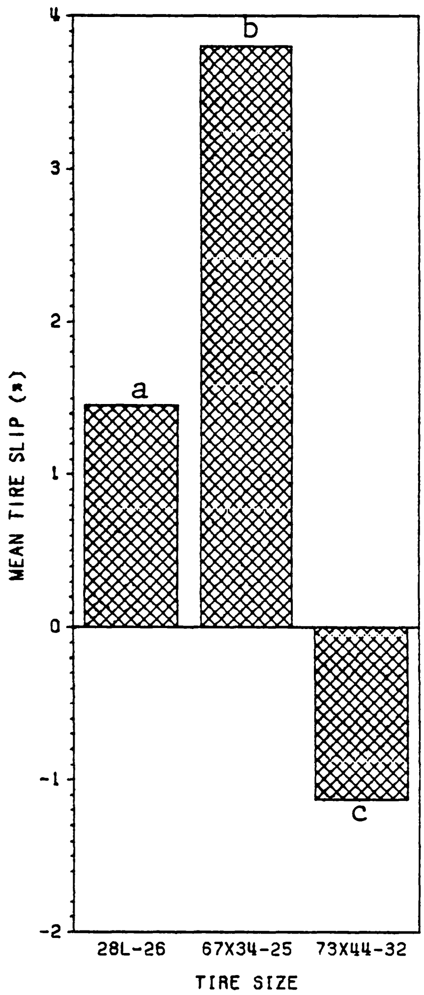


Figure 12. Mean tire slip by tire size (moist trial): Means pooled across blocks and passes. Means with the same letter were not significantly different ($\alpha = 0.10$).

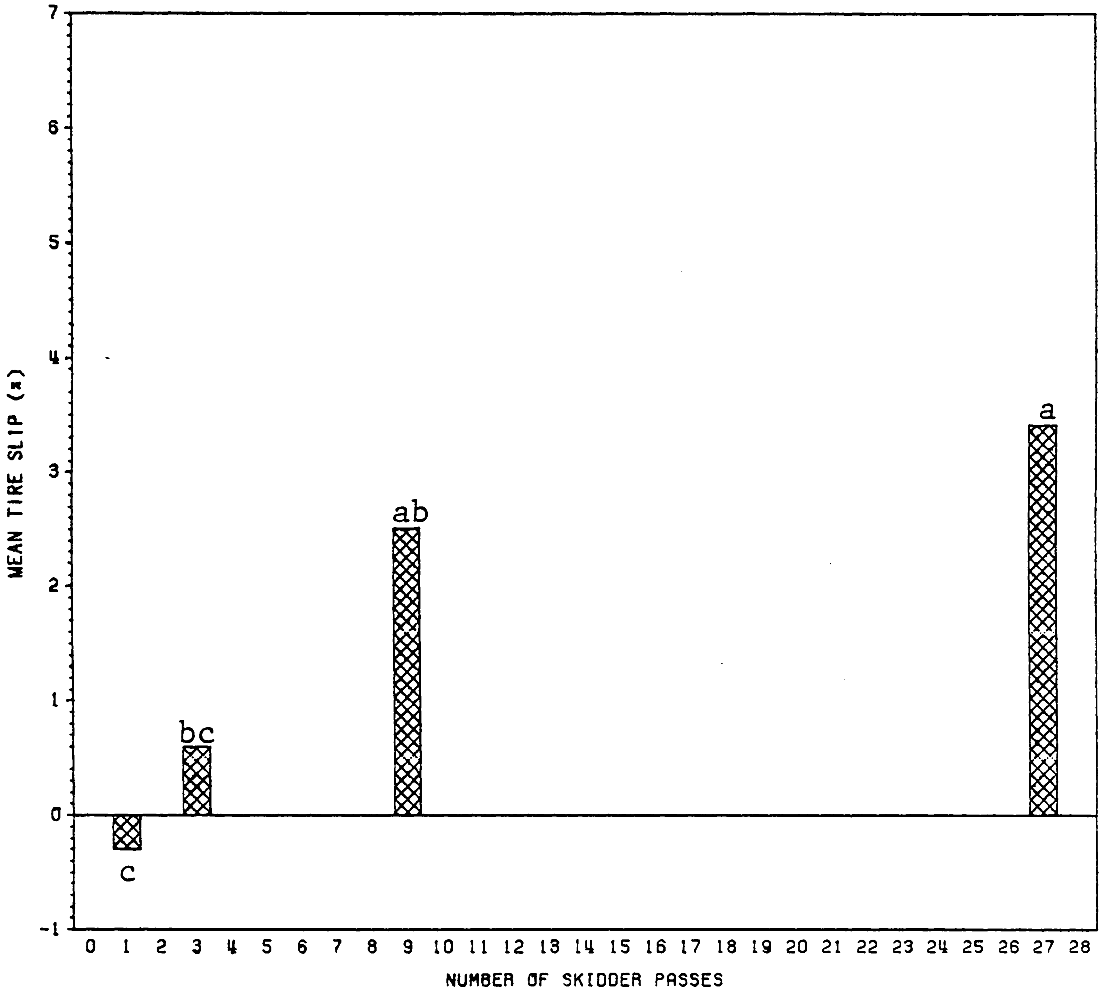


Figure 13. Mean tire slip by pass (moist trial): Mean pooled across blocks and tires. Means with the same letter were not significantly different ($\alpha = 0.10$).

Soil Bulk Density

Mean soil bulk density values before skidding ranged from 1.16 to 1.40 g/cc, while after skidding values ranged from 1.23 to 1.62 g/cc (Table 8).

The only treatment which influenced differences in bulk density was the number of skidder passes ($p = 0.0009$) (Table 9). The difference in bulk density increased from 0.03 g/cc at pass 1 to 0.25 g/cc at pass 27 (Figure 14). The impact on differences in bulk density for passes 1 and 3 was similar; the mean difference in bulk density was 0.03 and 0.10 g/cc at 1 and 3 passes, respectively. There was a greater influence on difference in bulk density at 9 and 27 passes, with the mean difference being 0.20 and 0.25 g/cc, respectively. This indicated the majority of increase in the difference in bulk density occurred prior to 9 passes. This conclusion supported the findings of Hatchell et al. 1970, Greene 1983, and Burger et al. 1985. The effect from tire size on differences in bulk density was indistinguishable.

The economic and biological importance of the increases in bulk density were not known, but may be investigated in the future. Critical growth limiting bulk density values are difficult to determine since factors such as tree species, moisture characteristics, particle size distribution, organic matter content, and nutrient status must all be considered.

Soil Porosity

Mean non-capillary pore space ranged from 11.10 to 19.80% before skidding, and 6.03 to 21.17% after skidding (Table 10). Non-capillary pore space was affected by the number of skidder passes (Table 11). One pass had little affect on non-capillary pore space, whereas the effect from 3, 9, and 27 passes was more pronounced (Figure 15).

Table 8. Bulk density before and after skidding (moist trial)

Block	Tire size	Pass	Mean Bulk Density (g/cc) Before skidding[1]	After skidding[2]
1	28L-26	1	1.33	1.27
	28L-26	3	1.22	1.29
	28L-26	9	1.22	1.48
	28L-26	27[3]	-	-
	67x34-25	1	1.33	1.27
	67x34-25	3	1.26	1.49
	67x34-25	9	1.26	1.61
	67x34-25	27	1.30	1.62
	73x44-32	1	1.22	1.30
	73x44-32	3	1.22	1.30
	73x44-32	9	1.33	1.40
	73x44-32	27[3]	-	-
2	28L-26	1	1.34	1.28
	28L-26	3	1.29	1.33
	28L-26	9	1.29	1.35
	28L-26	27	1.29	1.53
	67x34-25	1	1.29	1.36
	67x34-25	3	1.34	1.33
	67x34-25	9	1.29	1.37
	67x34-25	27	1.26	1.59
	73x44-32	1	1.34	1.35
	73x44-32	3	1.25	1.23
	73x44-32	9	1.25	1.35
	73x44-32	27	1.26	1.52
3	28L-26	1	1.16	1.37
	28L-26	3	1.16	1.37
	28L-26	9	1.16	1.51
	28L-26	27	1.40	1.51
	67x34-25	1	1.29	1.37
	67x34-25	3	1.29	1.43
	67x34-25	9	1.16	1.48
	67x34-25	27	1.33	1.59
	73x44-32	1	1.29	1.31
	73x44-32	3	1.33	1.49
	73x44-32	9	1.26	1.51
	73x44-32	27	1.26	1.51

[1] Mean within six adjacent skid zones at depth closest to which "after skidding" sample was taken.
[2] Mean within each skid zone.
[3] Pass treatment not properly completed.

Table 9. Mean difference in soil bulk density by tire size and pass (moist trial)

Pass	Mean[1] difference in bulk density (g/cc)			Mean[2] across tire
	Tire size			
	28L-26	67x34-25	73x44-32	
1	0.03	0.03	0.03	0.03 (B)
3	0.11	0.12	0.07	0.10 (B)
9	0.22	0.25	0.14	0.20 (A)
27	0.17[3]	0.30	0.25[3]	0.25 (A)
Mean[2] across pass	0.13 (a)	0.18 (a)	0.11 (a)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).
[3] based on 2 observations.

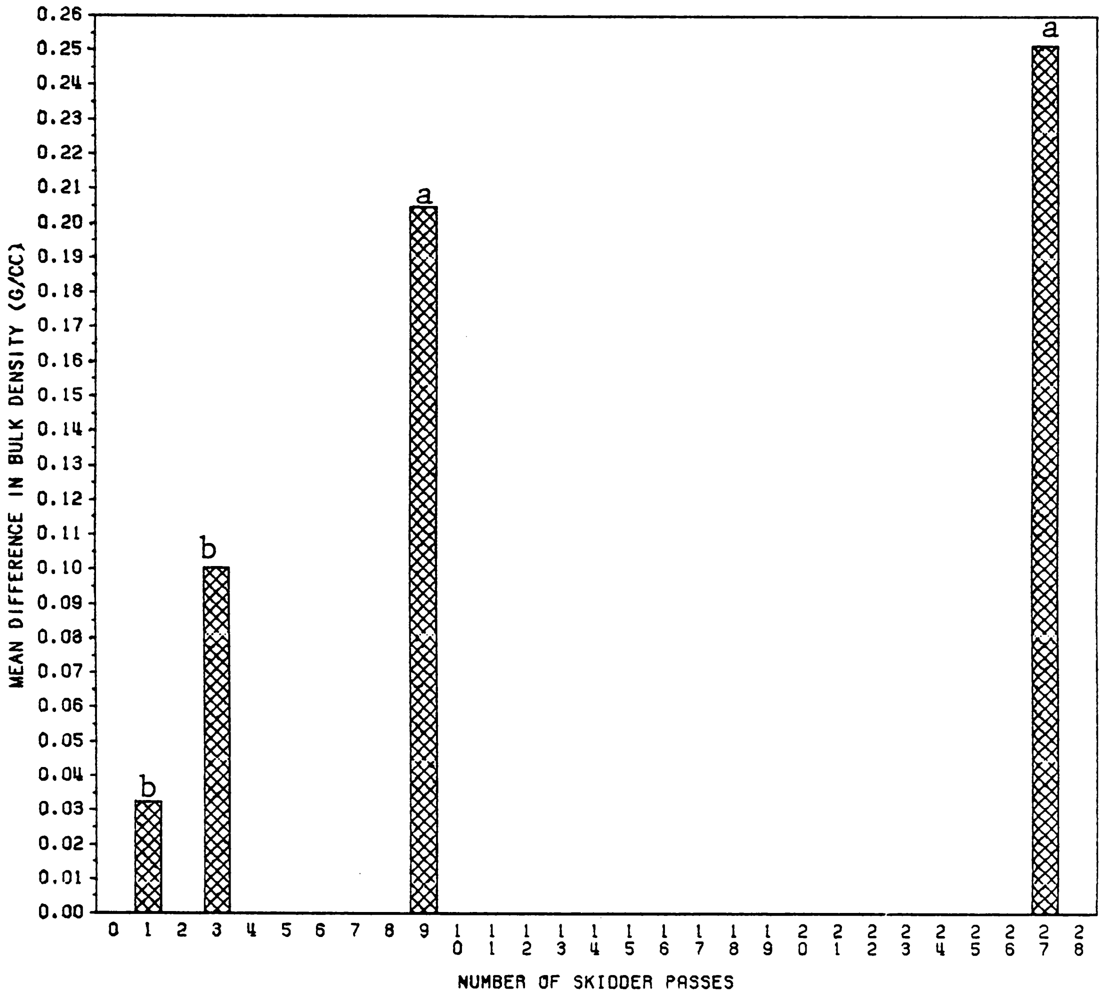


Figure 14. Mean difference in bulk density by pass (moist trial): Mean pooled across blocks and tires. Means with the same letter were not significantly different ($\alpha = 0.10$).

Table 10. Non-capillary pore space before and after skidding (moist trial)

Block	Tire size	Pass	Mean Non-cap. pore space (%) Before skidding[1]	After skidding[2]
1	28L-26	1	15.40	21.17
	28L-26	3	15.40	14.20
	28L-26	9	15.40	6.87
	28L-26	27[3]	-	-
	67x34-25	1	15.40	20.17
	67x34-25	3	15.90	6.70
	67x34-25	9	15.90	8.10
	67x34-25	27	13.00	6.83
	73x44-32	1	15.40	13.20
	73x44-32	3	15.40	12.97
	73x44-32	9	15.40	10.53
	73x44-32	27[3]	-	-
2	28L-26	1	12.00	13.70
	28L-26	3	12.60	12.63
	28L-26	9	12.60	10.10
	28L-26	27	12.60	6.20
	67x34-25	1	12.60	11.47
	67x34-25	3	12.00	10.43
	67x34-25	9	12.60	10.77
	67x34-25	27	12.80	6.27
	73x44-32	1	12.00	9.50
	73x44-32	3	18.60	17.00
	73x44-32	9	18.60	10.93
	73x44-32	27	12.80	6.03
3	28L-26	1	19.80	12.13
	28L-26	3	19.80	8.60
	28L-26	9	19.80	9.13
	28L-26	27	11.10	8.63
	67x34-25	1	15.70	13.17
	67x34-25	3	15.70	7.60
	67x34-25	9	19.80	7.70
	67x34-25	27	12.90	6.50
	73x44-32	1	15.70	17.13
	73x44-32	3	12.90	7.07
	73x44-32	9	14.90	7.07
	73x44-32	27	14.90	7.80

[1] Mean within six adjacent skid zones at depth closest to which after sample was taken.
[2] Mean within each skid zone.
[3] Pass treatment not properly completed

Generally, non-capillary pore space less than 10% has been considered detrimental to tree growth (Terry and Campbell 1981). None of the before skidding non-capillary values were considered detrimental to tree growth, whereas 5 of 9 values after 9 passes and all values after 27 passes had non-capillary pore space values less than 10%. Site preparation may ameliorate some of the lost non-capillary pore space, but it is recommended that pass levels greater than 9 be avoided. It is recommended that skidding be dispersed over the site to avoid higher pass levels.

The mean percent difference in non-capillary pore space was 0.3 at pass 1, compared to 4.6, 7.1, and 6.0 at 3, 9, and 27 passes, respectively. Operating the skidder with the three different tire sizes did not influence differences in non-capillary pore space of the soil.

The number of skidder passes affected soil total pore space in the same manner as bulk density since total pore space was calculated from bulk density. Mean decrease in total pore space was 1.2, 3.7, 7.7 and 9.6% at 1, 3, 9, and 27 passes respectively. Capillary pore space, being the difference in total and non-capillary pore space, was also affected by number of skidder passes. One, 3, and 9 skidder passes caused only minor differences in capillary pore space of -0.9, 0.8, and -0.6%, respectively. The 27 pass treatment had a greater influence, resulting in a difference of -3.6%.

Saturated Hydraulic Conductivity

Mean saturated hydraulic conductivity ranged from 9.06 to 126.10 cm/hr before skidding, and 0.07 to 80.16 cm/hr after skidding (Table 12).

The number of skidder passes affected differences in soil saturated hydraulic conductivity (Table 13). The effect of 1, 3, and 9 skidder passes was similar, while there was a greater decrease at 27 passes (Figure 16). The difference in the rate of water drainage through the soils on the study site decreased by 15.13, 27.21, 35.32, and 70.35 cm/hr, at 1, 3, 9, and 27 passes, respectively.

Table 11. Mean difference in non-capillary pore space by tire size and pass (moist trial)

Pass	Mean[1] difference in non-cap. pore space (%)			Mean[2] across tire
	Tire size			
	28L-26	67x34-25	73x44-32	
1	-0.07	0.37	-1.09	-0.26 (A)
3	-4.12	-6.29	-3.29	-4.57 (B)
9	-7.23	-7.24	-6.79	-7.09 (B)
27	-4.43[3]	-6.37	-6.93[3]	-5.98 (B)
Mean[2] across pass	-3.92 (a)	-4.88 (a)	-4.31 (a)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).
[3] based on 2 observations.

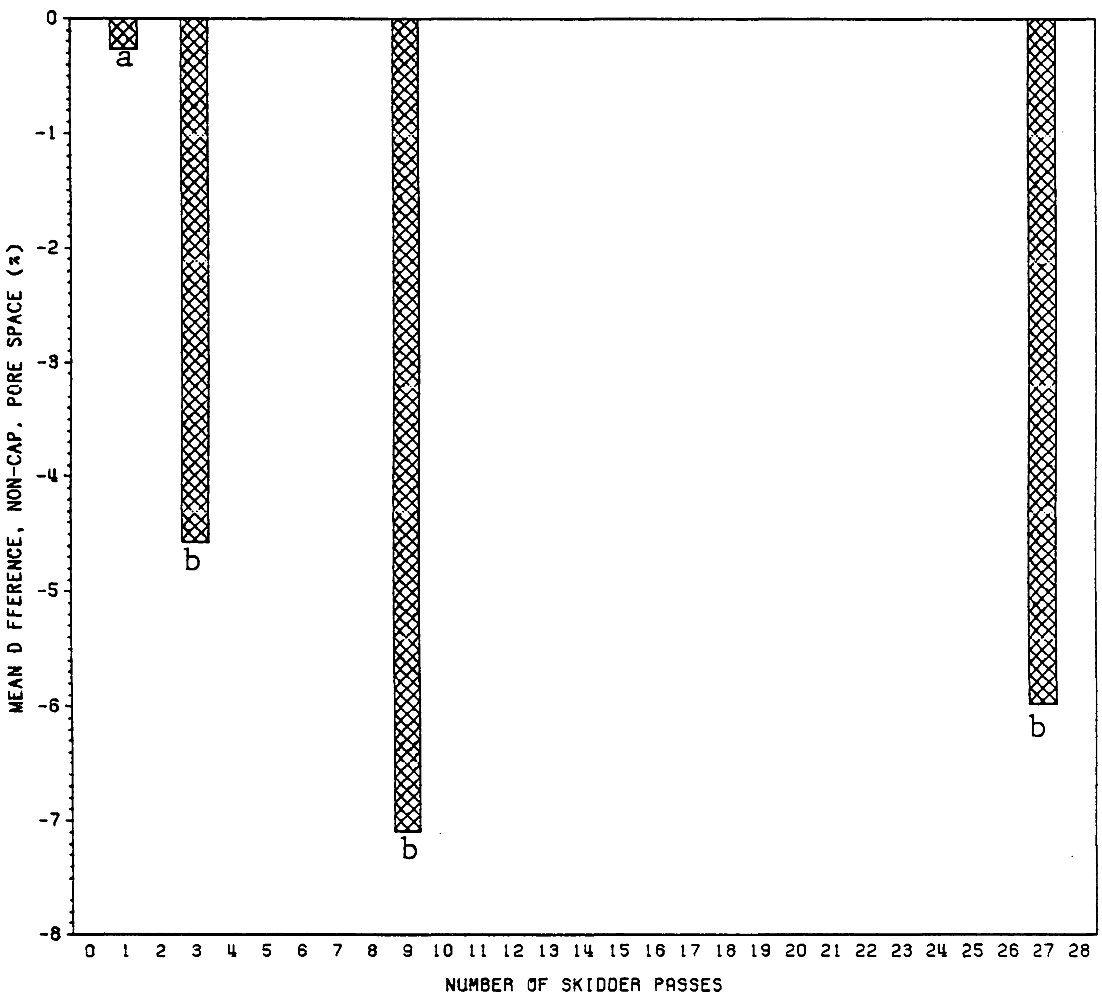


Figure 15. Mean difference in non-capillary pore space by pass (moist trial): Mean pooled across blocks and tires. Means with the same letter were not significantly different ($\alpha = 0.10$).

Table 12. Saturated hydraulic conductivity before and after skidding (moist trial)

Block	Tire size	Pass	Mean Sat. K (cm/hour)	
			Before skidding[1]	After skidding[2]
1	28L-26	1	55.99	48.70
	28L-26	3	56.99	14.83
	28L-26	9	56.99	2.86
	28L-26	27[3]	-	-
	67x34-25	1	55.99	80.16
	67x34-25	3	42.47	0.22
	67x34-25	9	42.47	0.15
	67x34-25	27	126.10	0.13
	73x44-32	1	56.99	10.89
	73x44-32	3	56.99	11.73
	73x44-32	9	55.99	13.38
	73x44-32	27[3]	-	-
2	28L-26	1	9.06	24.48
	28L-26	3	27.80	12.09
	28L-26	9	27.80	8.63
	28L-26	27	27.80	2.54
	67x34-25	1	27.80	11.27
	67x34-25	3	9.06	7.45
	67x34-25	9	27.80	4.95
	67x34-25	27	118.40	0.17
	73x44-32	1	9.06	10.46
	73x44-32	3	11.24	19.12
	73x44-32	9	11.24	6.36
	73x44-32	27	118.40	1.35
3	28L-26	1	32.55	7.45
	28L-26	3	32.55	6.27
	28L-26	9	32.55	0.45
	28L-26	27	17.16	1.11
	67x34-25	1	57.81	10.66
	67x34-25	3	57.81	1.91
	67x34-25	9	32.55	0.67
	67x34-25	27	25.18	0.17
	73x44-32	1	57.81	22.80
	73x44-32	3	25.18	1.61
	73x44-32	9	70.38	2.48
	73x44-32	27	70.38	0.07

[1] Mean within six adjacent skid zones at depth closest to which after sample was taken.
[2] Mean within each skid zone.
[3] Pass treatment not properly completed

Table 13. Mean difference in saturated hydraulic conductivity by tire size and pass (moist trial)

Pass	Mean[1] difference in Sat.K. (cm/hr)			Mean[2] across tire
	Tire size			
	28L-26	67x34-25	73x44-32	
1	-5.66	-13.17	-26.57	-15.13 (A)
3	-28.05	-33.25	-20.32	-27.21 (A)
9	-35.13	-32.35	-38.46	-35.32 (A)
27	-18.65[3]	-89.74	-93.68[3]	-70.55 (B)
Mean[2] across pass	-22.17 (a)	-42.13 (a)	-40.31 (a)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).
[3] based on 2 observations.

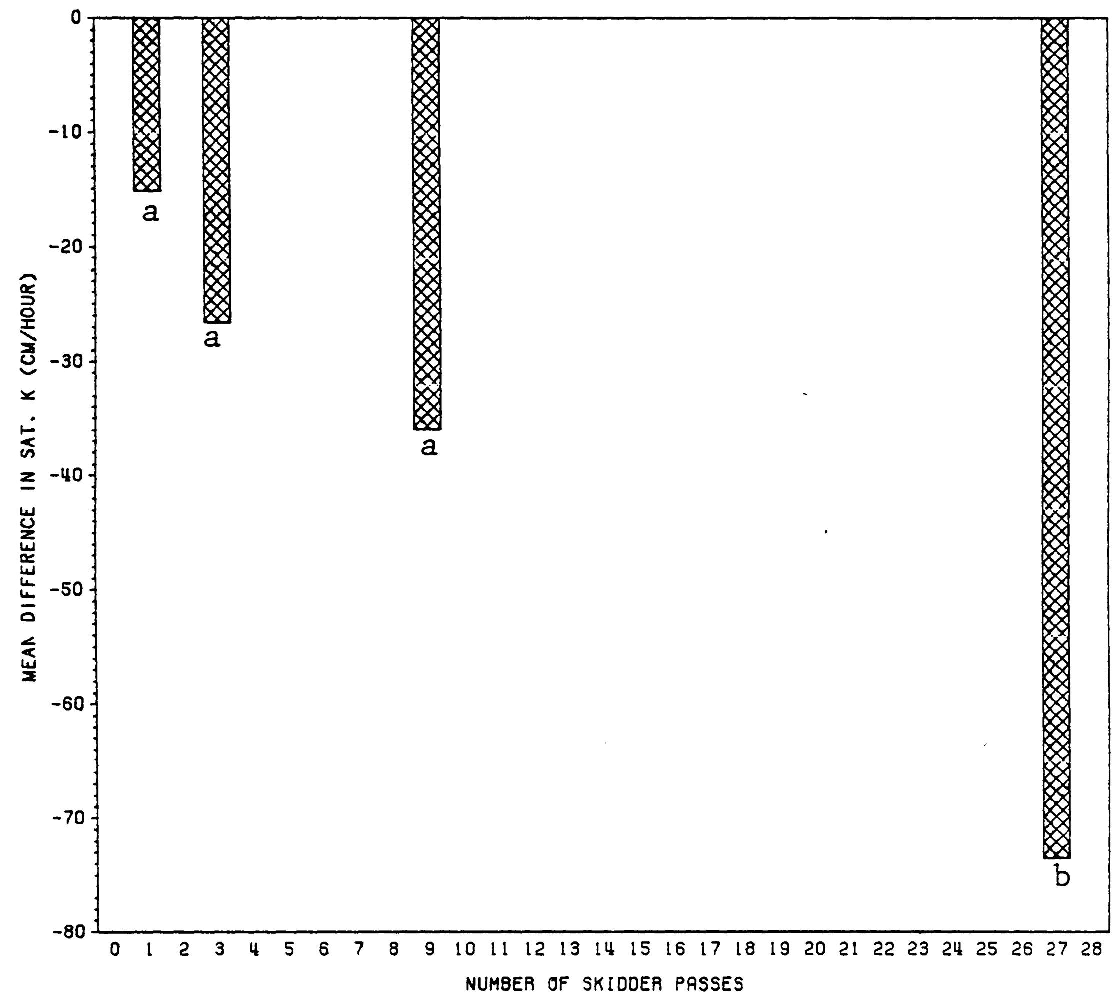


Figure 16. Mean difference in saturated hydraulic conductivity by pass (moist trial): Mean pooled across blocks and tires. Means with the same letter were not significantly different ($\alpha = 0.10$).

With the low mean saturated hydraulic conductivity values after 27 passes of 0.79 cm/hr, coupled with the transpirational loss from the harvested trees, the logging site will not drain as fast. Since soil moisture is critical to future management operations such as site preparation, maintenance of soil drainage ability should be considered during harvest planning. To maintain soil drainage, skidder pass levels across a certain soil area should not exceed 9 passes if possible.

With moist soil conditions tire size selection provided no means to influence differences in saturated hydraulic conductivity.

Rut Profiles

Only the compaction and disturbance rut profile measurement variables were analyzed since the churn and rut variables did not apply to the moist (July) trial (see Appendix A for definitions of the rut variables).

The number of skidder passes affected the area of compaction as measured with the rut profiles (Table 14). Mean compaction was -0.31 and -0.04 ft^2 (-0.03 and -0.004 m^2) at 1 and 3 passes, respectively (Figure 17). The negative values indicated a slight tillage effect of the ground surface. At 9 and 27 passes, the skidder produced a small compaction effect of 0.46 and 0.69 ft^2 (0.04 and 0.06 m^2), respectively. These small compaction or tillage effects were very difficult to detect visually in the field. Area of compaction was not affected by the three different tire sizes ($p = 0.9208$).

Area of disturbance was affected by number of skidder passes ($p = 0.0006$) (Table 15). Mean disturbance was 0.72, 0.64, 1.21, and 1.75 ft^2 (0.07, 0.06, 0.11, and 0.16 m^2) at 1, 3, 9, and 27 passes, respectively. (Figure 18). It was evident that tire size had little effect on disturbance with the moist soil condition. On the other hand, the increase in disturbance area by number of skidder passes was measurable as well as visually detectable. At 1 and 3 passes it was difficult to determine the

Table 14. Mean compaction area by tire size and pass (moist trial)

Pass	Mean[1] compaction area (ft^2) Tire size 28L-26	67x34-25	73x44-32	Mean[3] across tire
1	-0.53	-0.07	-0.35	-0.31 (C)
3	0.00	-0.07	-0.07	-0.04 (BC)
9	0.61	0.54	0.24	0.46 (AB)
27	0.60[4]	0.32	1.35[4]	0.69 (A)
Mean[3] across pass	0.13 (a)	0.18 (a)	0.20 (a)	

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).
[4] based on 2 observations.

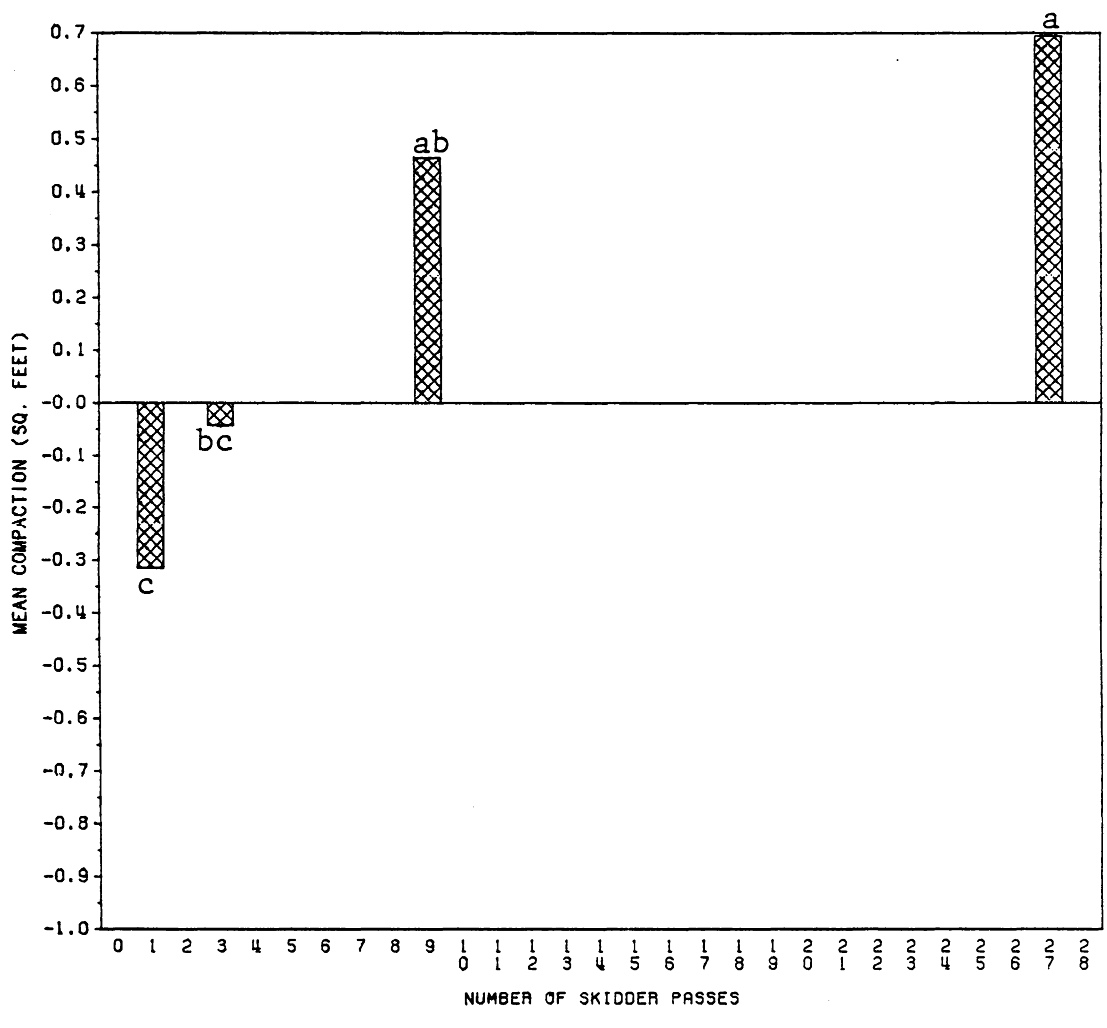


Figure 17. Mean compaction area by pass (moist trial): Mean pooled across blocks and tires. Means with the same letter were not significantly different ($\alpha = 0.10$).

exact location of the skidder tire tracks upon visual inspection in the field. By 9 passes the tire tracks became visible and at 27 passes their location was noticeable but not unsightly (Figure 19).

Cone Index

Mean cone index values before and after skidding are found in Table 16. Mean difference in cone index was affected by tire size (Table 17). The 28L-26 tire increased mean cone index after skidding by 21 psi (145 kPa), while the 67x34-25 and 73x44-32 tires decreased mean cone index by 44 (303 kPa) and 9 psi (62 kPa), respectively (Figure 20). There was no apparent effect on differences in cone index by number of skidder passes.

Moisture content has been found to be critical to cone index measurements, with an increase in moisture content resulting in decreased penetration resistance (Perumpral 1983). There was a high negative correlation between moisture content and mean difference in cone index ($r = -0.61$, $p = 0.0001$). The skid zones which received the 67x34-25 tire treatment had a slightly higher soil moisture which related to the greater decrease in cone index values. As the cone index values changed little, the impact on resistance to root penetration was not evident.

Wet (September) Trial

General Description

Pre-treatment soil moisture content ranged from 28.5 to 35.3% with an average of 31.6%. The 67x34-25 tire treatment occurred between September 8th and 10th, 1986. The 73x44-32 tire treatment was postponed until September 24th, 1986 after 1.27 in (3.2 cm) of rainfall occurred between

Table 15. Mean disturbance area by tire size and pass (moist trial)

Pass	Mean[1] disturbance area (ft^2)			Mean[3] across tire
	Tire size			
	28L-26	67x34-25	73x44-32	
1	0.49	0.88	0.80	0.72 (C)
3	0.82	0.73	0.37	0.64 (C)
9	1.17	1.39	1.06	1.21 (B)
27	1.43[4]	1.77	2.05[4]	1.75 (A)
Mean[3] across pass	0.94 (a)	1.19 (a)	0.98 (a)	

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).
[4] based on 2 observations.

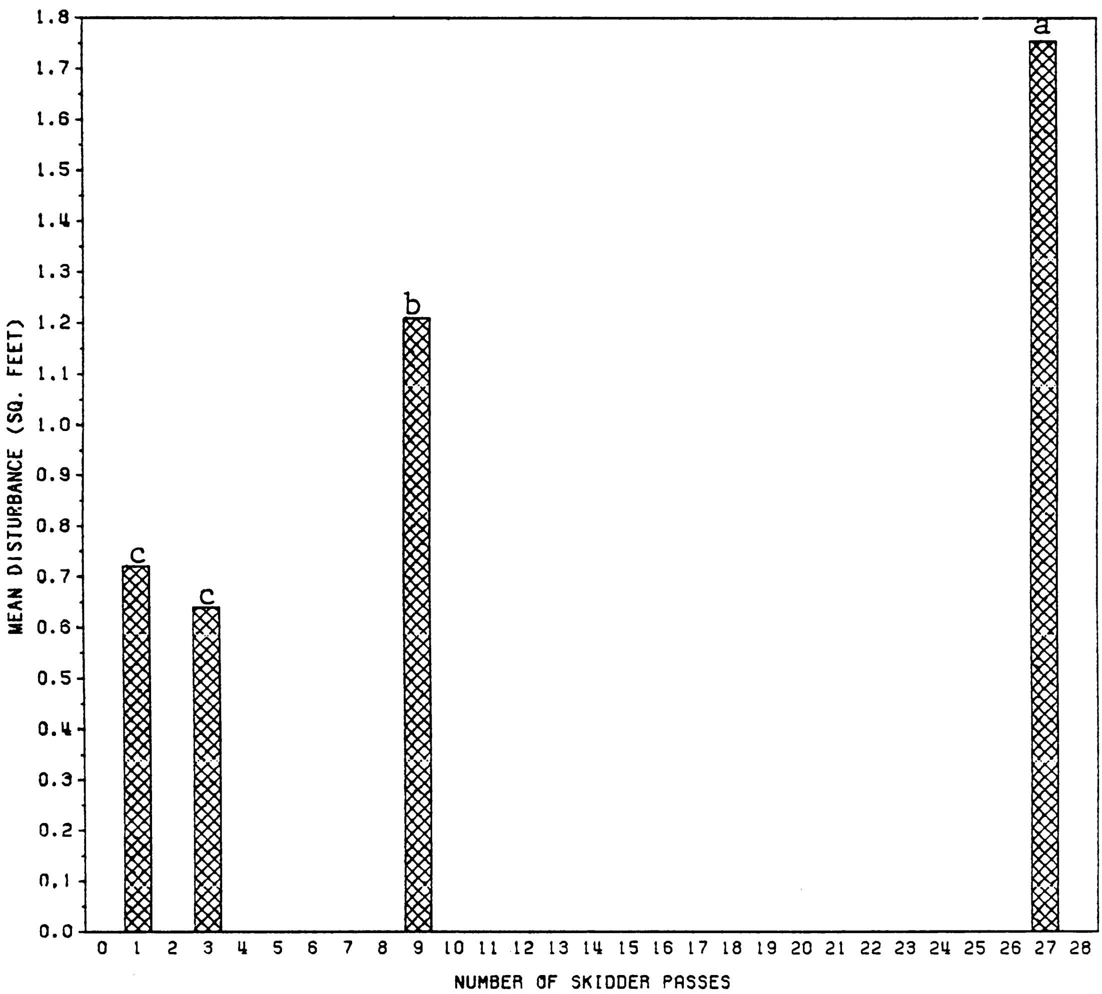


Figure 18. Mean disturbance area by pass (moist trial): Mean pooled across blocks and tires. Means with the same letter were not significantly different ($\alpha = 0.10$).

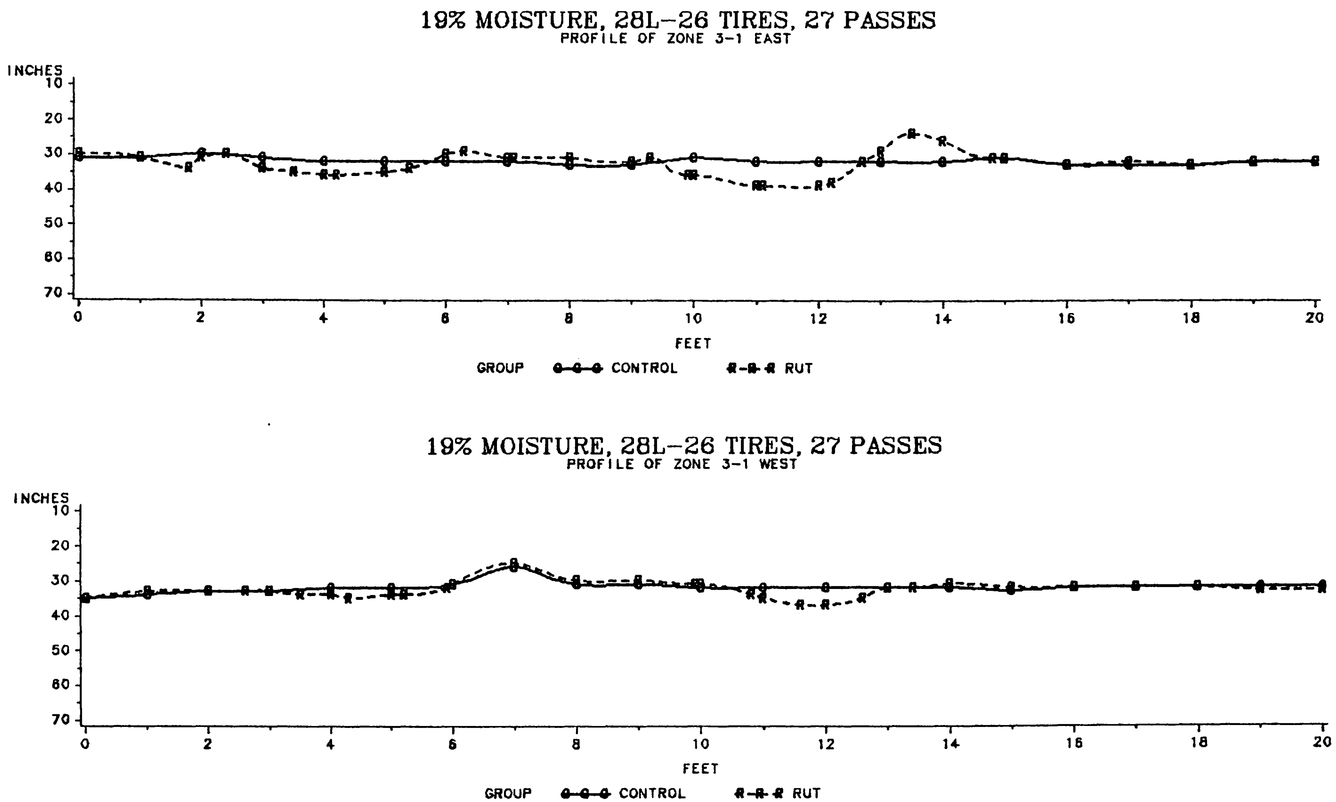


Figure 19. Example rut profile (moist trial): 28L-26 tires at 27 passes

Table 16. Cone index before and after skidding (moist trial)

Block	Tire size	Pass	Mean[1] Cone Index (psi) Before skidding	After skidding
1	28L-26	1	154.8	181.7
	28L-26	3	212.1	237.1
	28L-26	9	156.9	270.4
	28L-26	27[2]	-	-
	67x34-25	1	190.0	181.5
	67x34-25	3	110.2	50.0
	67x34-25	9	120.0	30.0
	67x34-25	27	110.2	47.3
	73x44-32	1	298.5	278.3
	73x44-32	3	289.0	310.6
	73x44-32	9	139.6	186.3
	73x44-32	27[2]	-	-
2	28L-26	1	153.5	149.2
	28L-26	3	199.6	192.7
	28L-26	9	173.3	216.5
	28L-26	27	163.1	326.5
	67x34-25	1	226.0	198.3
	67x34-25	3	158.1	143.5
	67x34-25	9	187.1	226.3
	67x34-25	27	161.9	74.2
	73x44-32	1	135.2	123.5
	73x44-32	3	212.5	211.5
	73x44-32	9	181.7	213.8
	73x44-32	27	143.1	103.5
3	28L-26	1	126.5	95.2
	28L-26	3	100.8	85.6
	28L-26	9	109.2	54.8
	28L-26	27	127.1	102.3
	67x34-25	1	105.8	99.8
	67x34-25	3	113.3	44.6
	67x34-25	9	112.5	50.0
	67x34-25	27	132.9	60.0
	73x44-32	1	126.7	111.3
	73x44-32	3	129.4	124.6
	73x44-32	9	147.1	133.5
	73x44-32	27	119.6	31.0

[1] Mean within each skid zone across the four sample locations
[2] Pass treatment not properly completed

Table 17. Mean cone index difference by tire size and pass (moist trial)

Pass	Mean[1] cone index difference (psi) Tire size 28L-26	67x34-25	73x44-32	Mean[2] across tire
1	-2.9	-14.1	-15.8	-10.9 (A)
3	1.0	-47.8	5.3	-13.9 (A)
9	34.1	-38.0	21.7	6.0 (A)
27	69.3[3]	-74.5	-64.1[3]	-30.4 (A)
Mean[2] across pass	21.4 (a)	-43.6 (b)	-8.6 (a)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).
[3] based on 2 observations.

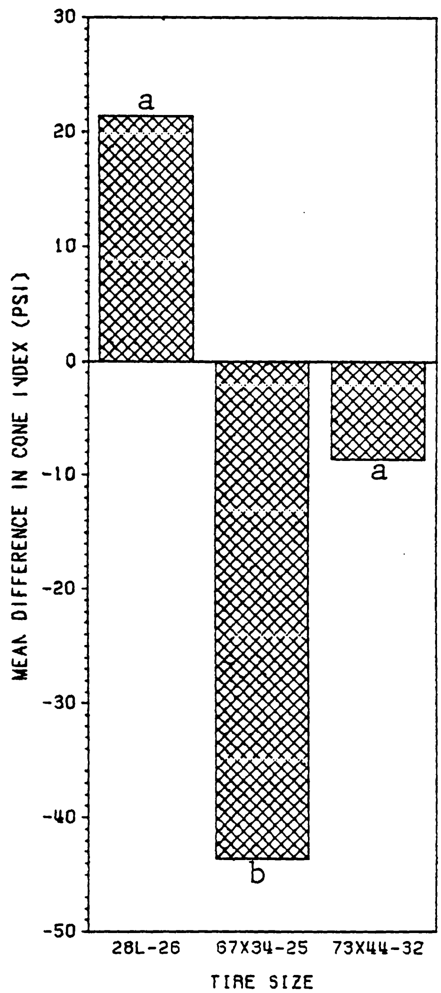


Figure 20. Mean difference in cone index by tire size (moist trial): Means pooled across blocks and passes. Means with the same letter were not significantly different ($\alpha = 0.10$).

September 9th and 10th. Water table depth averaged 2.8 in (7 cm) for the 67x34-25 tire treatment and 9.8 in (25 cm) for the 73x44-32 tire treatment. The skidder load averaged 6840 lb (3103 kg) and 6783 lb (3077 kg) for the 67x34-25 and 73x44-32 tire treatments, respectively. Skidder and tire specifications are listed in Appendix F. The wet (September) trial data were subdivided into three analyses: tire size, operating gear, and tire size and operating gear.

Tire Size Comparison

Table 18 lists general information for comparing the performance of the 67x34-25 and 73x44-32 tires. The skidder was able to complete more passes when mounted with the 73x44-32 tires; the maximum number of passes attained using the 67x34-25 tires was 6, compared to 16 with the 73x44-32 tires. The field conditions when skidding with the two tire sizes was similar with respect to soil moisture content, but differed with water table depth. Water table depth may have confounded the performance comparison between the 67x34-25 and 73x44-32 tires; that is, the shallower water table during skidding with the 67x34-25 tires may have decreased soil strength reducing the number of passes attained. The actual effect of the difference in water table depth on tire size performance and number of skidder passes was unknown. The statistical analysis was made with the 67x34-25 and 73x44-32 tires at 1 and 3 passes with the skidder operated in second gear.

Skidder Speed

Since the 67x34-25 and 73x44-32 tires were both operated on the same skidder, differences in speed due to axle differential ratio and governed engine RPM did not exist. Skidder speed was affected only by number of passes (Table 19). Skidder speed with the two tire sizes was comparable; mean speed across passes was 259 and 269 ft/min (78.9 and 82.0 m/min) when skidding with the 67x34-25 and 73x44-32 tires, respectively. Mean speed across tires decreased from 339 ft/min (103.3 m/min)

Table 18. Tire size comparison information (wet trial)

Block	Item	Tire Size (second gear)	
		67x34-25	73x44-32
1	Skidder passes attained	1,2,3,3	1,3,6,8
	Total skidder passes	9	18
	Ave. water depth, in. (cm)	2.9 (7)	11.0 (28)
	Water table depth range, in.	0 to 6.7	3.1 to 18.5
	(cm)	(0 to 17)	(8 to 47)
2	Skidder passes attained	1,3,4,6	1,3,6,16
	Total skidder passes	14	26
	Ave. water depth, in. (cm)	4.2 (11)	12.0 (30)
	Water table depth range, in.	0.8 to 7.1	5.1 to 20.9
	(cm)	(2 to 18)	(13 to 53)
3	Skidder passes attained	1,3,6,6	1,3,6,9
	Total skidder passes	16	19
	Ave. water depth, in. (cm)	1.4 (4)	6.5 (17)
	Water table depth range, in.	+0.8 to 3.9	4.7 to 11.4
	(cm)	(+2 to 3.9)	(12 to 29)

at 1 pass, to 189 ft/min (57.6 m/min) at 3 passes (Figure 21). The decrease in speed at pass 3 resulted from an increase in tire slip. Linear correlation between speed and slip was -0.95 ($p=0.0001$).

The slower skidder speeds at multiple passes would increase the time required to pull a turn, as well as increase the occurrance of immobility. Both of these could reduce productivity during harvesting. Dispersing skidder traffic to avoid soil rutting as is commonly done, may prolong operations and maintain higher travel speeds under wet soil conditions.

Tire Slip

The number of skidder passes had a significant affect on tire slip (Table 20). Tire slip while skidding with the 67x34-25 and 73x44-32 tires was similar, whereas mean slip increased from 7% at pass 1, to 37% at pass 3 (Figure 22). Between 1 and 3 passes, tire slip sheared the litter layer and soil surface, reducing soil strength. With multiple passes over a specific soil area, wheel slip increased dramatically which may increase wear and tear on the equipment, as well as increase down time while stuck. Again, dispersing skidder traffic as is commonly done on similar sites, appears to provide a means to maintain operability.

Rut Profiles

Compaction area was affected by tire size (Table 21). Mean compaction area was 0.49 and -0.67 ft^2 (0.05 and -0.06 m^2) during skidding with the 67x34-25 and 73x44-32 tires, respectively (Figure 23); however, the differences were minimal. Skidding with the 67x34-25 tires produced a small compaction effect; there was a net loss of area across the rut profile. Operation with the 73x44-32 tires was just the opposite; there was a net gain in area. This net gain in area was due

Table 19. Mean skidder speed by tire size and pass (wet trial)

Pass	Mean[1] speed (ft/min)		Mean[2] across tires
	Tire size		
	67x34-25	73x44-32	
1	346	332	339 (A)
3	171	207	189 (B)
Mean[2] across pass	259 (a)	269 (a)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

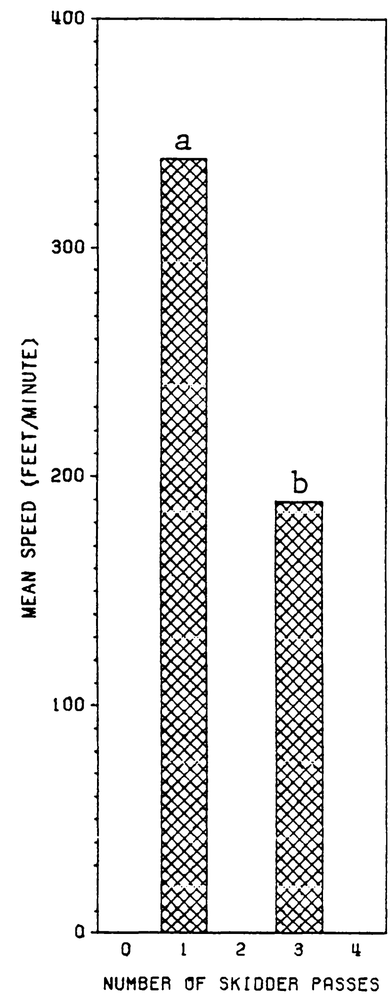


Figure 21. Mean skidder speed by pass (wet trial): Mean pooled across blocks and tires. Means with the same letter were not significantly different ($\alpha = 0.10$).

Table 20. Mean tire slip by tire size and pass (wet trial)

Pass	Mean[1] tire slip (%) Tire size 67x34-25	73x44-32	Mean[2] across tires
1	9.1	4.8	7.0 (B)
3	39.9	34.6	37.3 (A)
Mean[2] across pass	24.5 (a)	19.7 (a)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

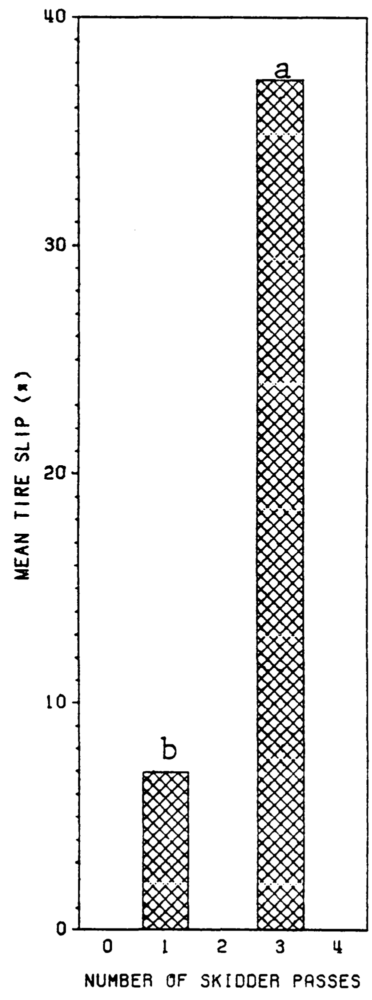


Figure 22. Mean tire slip by pass (wet trial): Mean pooled across blocks and tires. Means with the same letter were not significantly different ($\alpha = 0.10$).

either to translocation of soil and litter on top of the original surface between the rut stakes, or a tillage effect.

There was an interaction between tire size and number of skidder passes for disturbance area; that is, disturbance area at a given number of passes was affected by tire size (Table 22). Mean disturbance area increased from 2.28 to 10.12 ft^2 (0.21 to 0.94 m^2) between 1 and 3 passes, respectively, when skidding with the 67x34-25 tires, but did not change with increasing passes with the 73x44-32 tires.

Between 1 and 3 passes, the 73x44-32 tires maintained operation on the litter layer and soil surface, while the 67x34-25 tires "broke" through and sheared the soil to greater depth (Figure 24). Tire slip did not cause the greater disturbance exhibited by the 67x34-25 tires at pass 3, as slip between the two tire sizes was not different ($p = 0.8414$). Mean slip at pass 3 for the 67x34-25 tire was 40% compared to 35% for the 73x44-32 tire.

Rut area was affected by tire size and number of skidder passes (Table 23). Mean rut area was 1.80 and 1.14 ft^2 (0.17 and 0.11 m^2) after skidding using the 67x34-25 and 73x44-32 tires, respectively (Figure 25). The effect of the number of skidder passes on rut area is displayed in Figure 26. Rut area increased from 1.04 ft^2 (0.10 m^2) at pass 1, to 1.91 ft^2 (0.18 m^2) at pass 3.

Area of churned soil was affected by the number of skidder passes for a given tire size (Table 24). The rate of increase in churn area between 1 and 3 passes was more pronounced with the 67x34-25 tire, increasing from 1.82 to 9.60 ft^2 (0.17 to 0.89 m^2). Mean churn area was 5.14 and 6.05 ft^2 (0.48 and 0.56 m^2) after skidding with the 73x44-32 tires at 1 and 3 passes, respectively. Although the churn area was higher at pass 1 for the 73x44-32 tires, churn area did not increase significantly by pass 3. Area of churned soil was correlated with tire slip ($r = 0.74$, $p = 0.0063$). As tire slip increased, area of churned soil increased.

Table 21. Mean compaction area by tire size and pass (wet trial)

Pass	Mean[1] compaction area (ft^2) Tire size 67x34-25	73x44-32	Mean[3] across tires
1	0.46	-0.42	0.02 (A)
3	0.52	-0.92	-0.20 (A)
Mean[3] across pass	0.49 (a)	-0.67 (b)	

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

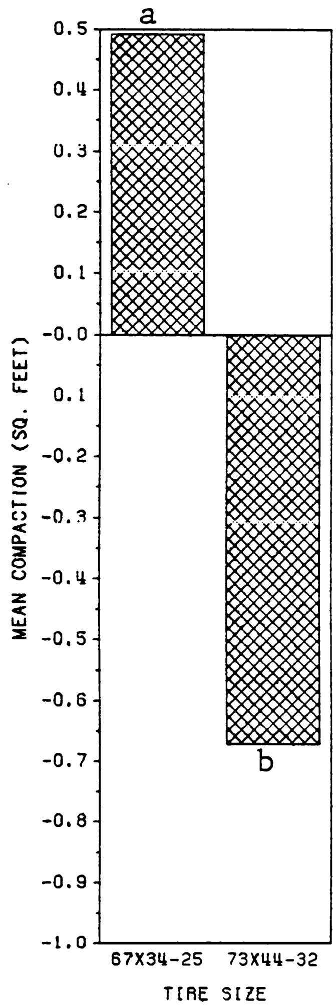
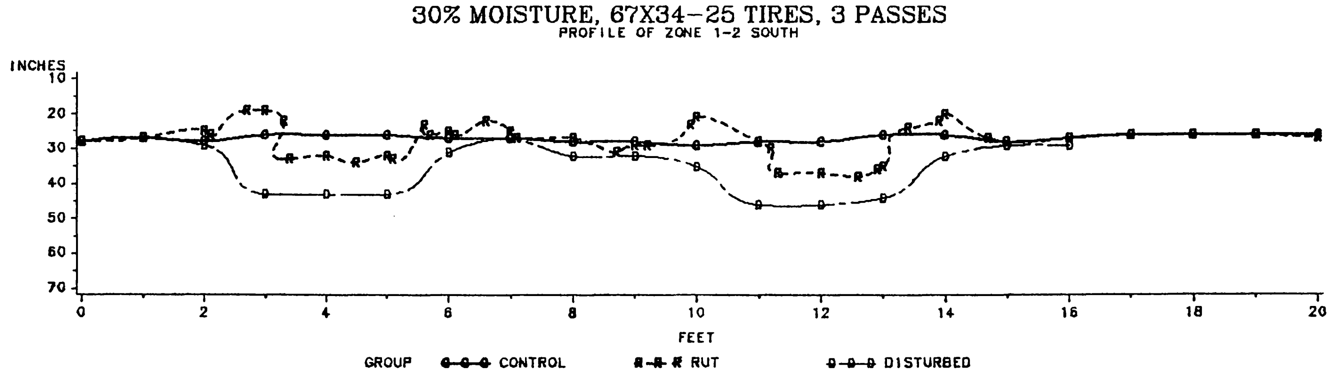


Figure 23. Mean compaction area by tire size (wet trial): Mean pooled across blocks and passes. Means with the same letter were not significantly different ($\alpha = 0.10$).

Table 22. Mean disturbance area by tire size and pass (wet trial)

Pass	Mean[1,3] disturbance area (ft^2) Tire size 67x34-25	73x44-32
1	2.28 (b)	4.71 (ab)
3	10.12 (a)	5.14 (ab)

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).



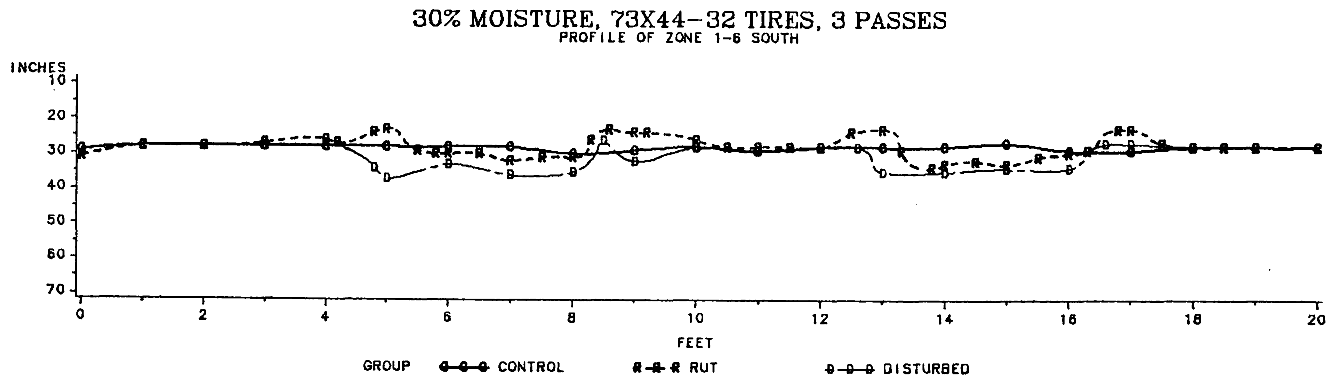


Figure 24. Example rut profile for 67x34-25 and 73x44-32 tires at 3 passes (wet trial)

Table 23. Mean rut area by tire size and pass (wet trial)

Pass	Mean[1] rut area (ft^2) Tire size 67x34-25	73x44-32	Mean[3] across tires
1	1.16	0.92	1.04 (B)
3	2.44	1.37	1.91 (A)
Mean[3] across pass	1.80 (a)	1.14 (b)	

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

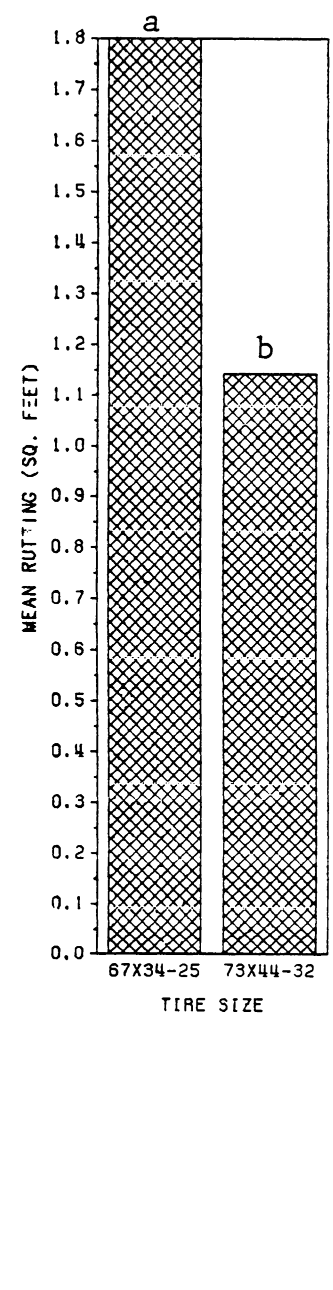


Figure 25. Mean rut area by tire size (wet trial): Mean pooled across blocks and passes. Means with the same letter were not significantly different ($\alpha = 0.10$).

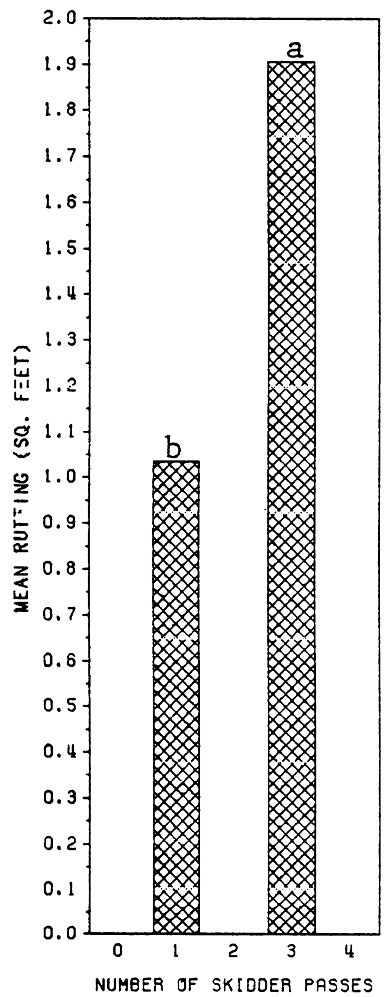


Figure 26. Mean rut area by pass (wet trial): Mean pooled across blocks and tires. Means with the same letter were not significantly different ($\alpha = 0.10$).

The rut profile measurements indicated that the 73x44-32 tires had less of an effect on the site than the 67x34-25 tires; compaction, disturbance, and rut areas were all less.

Cone Index

Mean cone index ranged from 48.1 to 109.0 psi (331.6 to 751.5 kPa) before skidding, and 4.0 to 45.2 psi 27.6 to 311.6 kPa) after skidding (Table 25). Difference in cone index after skidding was affected by the number of skidder passes for a given tire size (Table 26). For the 67x34-25 tires, increasing pass from 1 to 3 decreased difference in cone index from -31 to -56 psi (-213.7 and -386.1 kPa). Differences in cone index between 1 and 3 passes for the 73x44-32 tires were similar, -56 and -43 psi (-386.1 and -296.5 kPa), respectively. It was hypothesized that an increase in number of passes with wet soil conditions would increase the magnitude of difference in cone index, but this was not the case. The interaction between tire size and number of skidder passes on difference in cone index could not be explained. Difference in cone index was not correlated with any other variable.

Operating Gear Comparison

Table 27 lists general information for comparison of skidder operation in second and third gear using the 73x44-32 tires. The number of passes attained for the two operating gears within each block was similar, but it is important to note here that the skidding stopping rules were different. With second gear operation, the skidder was operated until the grapple had to be used to provide forward movement, whereas with third gear the skidder was operated until it was necessary to downshift to second gear. The operator also reduced engine RPM at his discretion to minimize wheel slip during third gear operation. With this difference in stopping rules, third gear operation

Table 24. Mean churn area by tire size and pass (wet trial)

	Mean[1],[3] churn area (ft^2)	
	Tire size	
Pass	67x34-25	73x44-32
1	1.82 (b)	5.14 (ab)
3	9.60 (a)	6.05 (ab)

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

Table 25. Cone index for the 67x34-25 and 73x44-32 tires at 1 and 3 passes (wet trial)

Block	Tire size	Pass	Mean[1] Cone Index (psi) Before skidding	After skidding
1	67x34-25	1	48.5	13.1
	67x34-25	3	69.8	19.4
	73x44-32	1	109.0	40.6
	73x44-32	3	57.7	32.3
2	67x34-25	1	77.5	45.2
	67x34-25	3	69.8	11.3
	73x44-32	1	66.0	18.8
	73x44-32	3	67.1	6.5
3	67x34-25	1	61.7	37.7
	67x34-25	3	84.2	26.5
	73x44-32	1	62.9	11.0
	73x44-32	3	48.1	4.0

[1] Mean within each skid zone across the four sample locations

Table 26. Mean cone index difference by tire size and pass (wet trial)

	Mean[1],[2] cone index difference (psi)	
	Tire size	
Pass	67x34-25	73x44-32
1	-30.6 (a)	-55.8 (b)
3	-55.6 (b)	-43.4 (ab)

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

appeared to have provided the potential to complete more passes if the skidder had been operated until the grapple had to be used.

Statistical comparisons were made with the skidder operated in second and third gears at 1 and 3 passes using the 73x44-32 tires. The hypothesis of the test was that lower wheel torque (lower engine RPM in third gear) would reduce tire slip, and decrease the rate of deterioration of the ability of the site to support skidder traffic.

Skidder Speed

Number of passes affected the speed of the skidder (Table 28). Since the skidder operator reduced engine RPM for third gear, there was not any difference in speed due to operating gear.

Mean skidder speed decreased from 337 ft/min (102.7 m/min) at pass 1 to 252 ft/min (76.8 m/min) at pass 3 (Figure 27). The decrease in speed between 1 and 3 passes for third gear operation was not as great as with second gear operation. Speed decreased from 343 to 297 ft/min (104.6 to 90.5 m/min) with third gear operation, compared to a decrease from 332 to 207 ft/min (101.2 to 63.1 m/min) with second gear, however this result was not significant. The primary factor relating to the reduction in speed at pass 3 was tire slip; the correlation between speed and slip for passes 1 and 3 was -0.90 ($p = 0.0001$).

Tire Slip

Tire slip was affected by the number of skidder passes for a given operating gear (Table 29). Slip at pass 1 was similar for second and third gear, but by 3 passes, tire slip with second gear was greater. This result was inherent to the way in which the skidder was operated; that is, the operator

Table 27. Operating gear comparison information (wet trial)

Block	Item	73x44-32 Tires	
		2nd Gear	3rd Gear
1	Skidder passes attained Total skidder passes Ave. water depth, in. (cm) Water table depth range, in. (cm)	1,3,6,8 18 11.0 (28) 3.1 to 18.5 (8 to 47)	1,3,3,9 16 11.0 (28) 3.1 to 18.5 (8 to 47)
2	Skidder passes attained Total skidder passes Ave. water depth, in. (cm) Water table depth range, in. (cm)	1,3,6,16 26 12.0 (30) 5.1 to 20.9 (13 to 53)	1,3,9,13 26 12.0 (30) 5.1 to 20.9 (13 to 53)
3	Skidder passes attained Total skidder passes Ave. water depth, in. (cm) Water table depth range, in. (cm)	1,3,6,9 19 6.5 (17) 4.7 to 11.4 (12 to 29)	1,3,8,8 20 6.5 (17) 4.7 to 11.4 (12 to 29)

Table 28. Mean skidder speed by operating gear and pass (wet trial)

Pass	Mean[1] speed (ft/min)		Mean[2] across gear
	73x44-32 tires		
	2nd gear	3rd gear	
1	332	343	337 (A)
3	207	297	252 (B)
Mean[2] across pass	269 (a)	320 (a)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

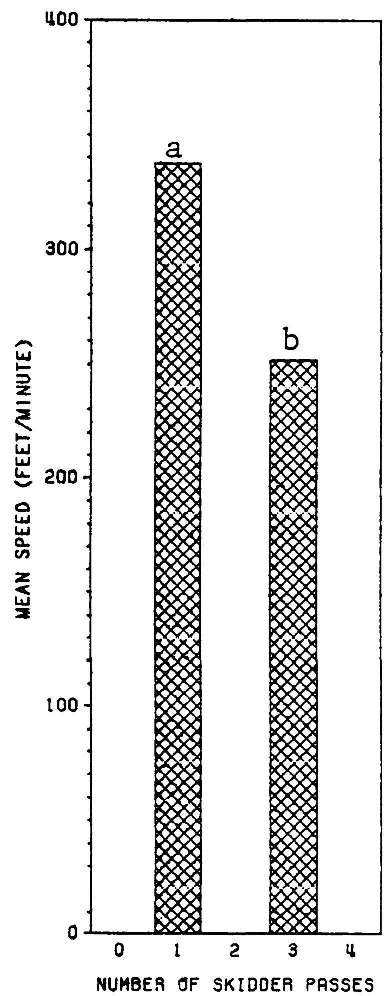


Figure 27. Mean skidder speed by pass (wet trial): Mean pooled across blocks and operating gears. Means with the same letter were not significantly different ($\alpha = 0.10$).

tried to minimize wheel slip while in third gear by adjusting engine RPM, while no attempt was made to minimize slip with second gear.

Slip at pass 1 was 5% for second gear and 4% for third gear. At pass 3 slip increased 7-fold to 35% for second gear, while slip with third gear only increased to 11%.

Rut Profiles

Operating the skidder in second or third gear, or at 1 or 3 passes did not affect area of compaction. Compaction area was also not affected by number of passes for a given operating gear (Table 30). All compaction areas indicated that a tillage effect had occurred. The magnitude of compaction was smallest with third gear operation at pass 1 and highest with second gear operation at pass 3; however, the differences were not significant.

Operating gear affected area of disturbance (Table 31). Mean disturbance with third gear was only 40% of the mean disturbance with second gear (Figure 28). Mean disturbance with second gear was 4.93 ft^2 (0.46 m^2), compared to 2.09 ft^2 (0.19 m^2) with third gear operation. Lower wheel torque from third gear operation reduced tire slip which lead to a decrease in the area of disturbance (Figure 29 and Figure 30). The correlation between disturbance and slip was 0.56 ($p = 0.0586$).

Rut area was affected by the number of skidder passes (Table 32). Mean rut area increased from 0.80 ft^2 (0.07 m^2) at pass 1 to 1.27 ft^2 (0.12 m^2) at pass 3 (Figure 31). This difference in rut area between 1 and 3 passes was minor and not easily detected in the field. The wet conditions of the soil did not allow large surface ruts to form because the churned soil tended to flow back into the rut.

The area of churned soil was affected by operating gear (Table 33). Mean area of churned soil was 5.60 ft^2 (0.52 m^2) with second gear, compared to 2.29 ft^2 (0.21 m^2) for third gear operation.

Table 29. **Mean tire slip by operating gear and pass (wet trial)**

	Mean[1],[2] slip (%)	
	73x44-32 tires	
Pass	2nd gear	3rd gear
1	4.8 (b)	3.8 (b)
3	34.6 (a)	10.7 (b)

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

Table 30. Mean compaction area by operating gear and pass (wet trial)

Pass	Mean[1] compaction area (ft^2) 73x44-32 tires 2nd gear	3rd gear	Mean[3] across gear
1	-0.42	-0.13	-0.28 (A)
3	-0.92	-0.27	-0.59 (A)
Mean[3] across pass	-0.67 (a)	-0.20 (a)	

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

Table 31. Mean disturbance area by operating gear and pass (wet trial)

Pass	Mean[1] disturbance area (ft^2) 73x44-32 tires 2nd gear	3rd gear	Mean[3] across gear
1	4.71	1.12	2.92 (A)
3	5.14	3.07	4.10 (A)
Mean[3] across pass	4.93 (a)	2.09 (b)	

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

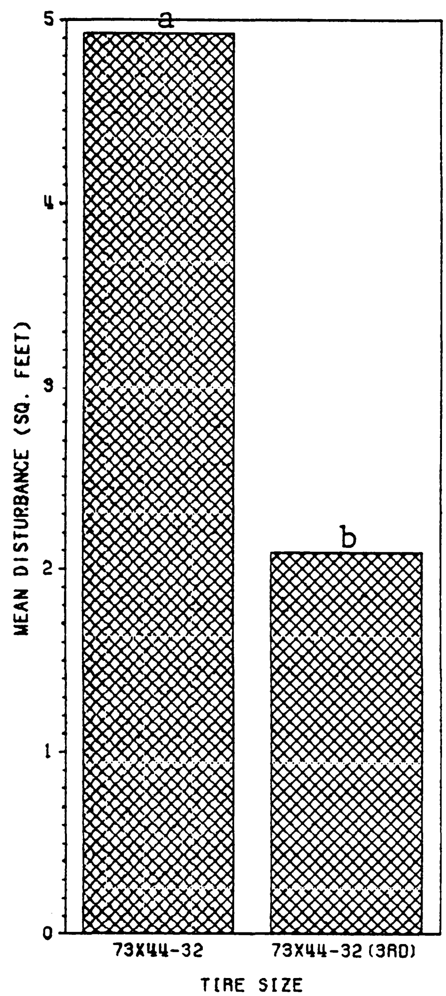
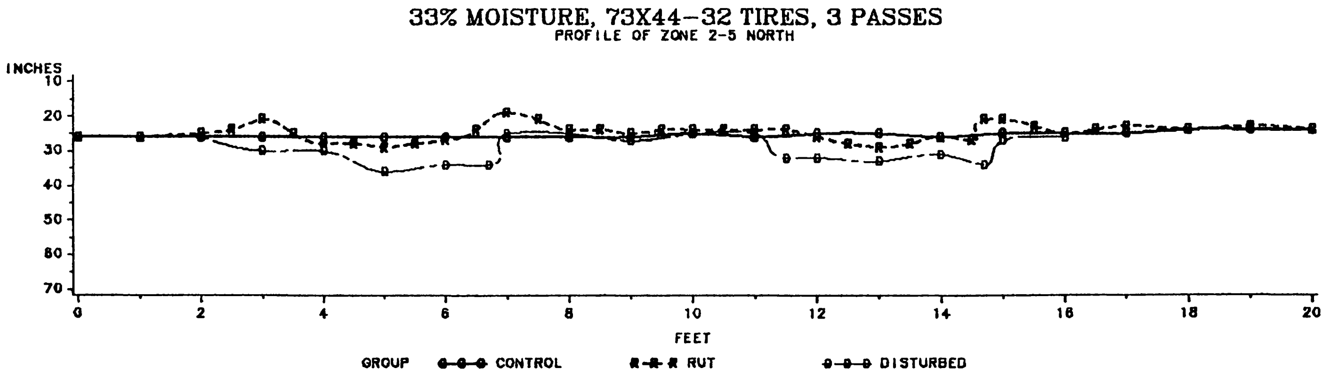


Figure 28. Mean disturbance area by operating gear (wet trial): Mean pooled across blocks and passes. Means with the same letter were not significantly different ($\alpha = 0.10$)



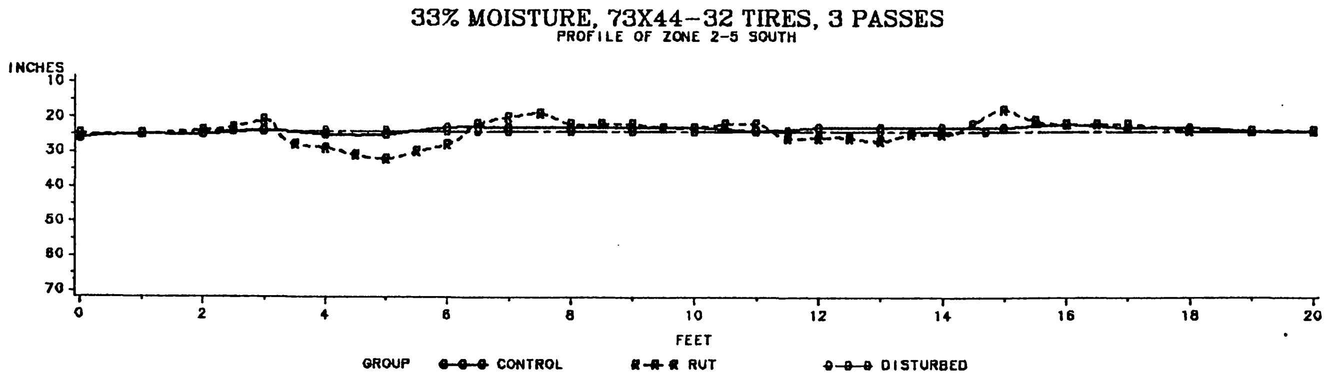
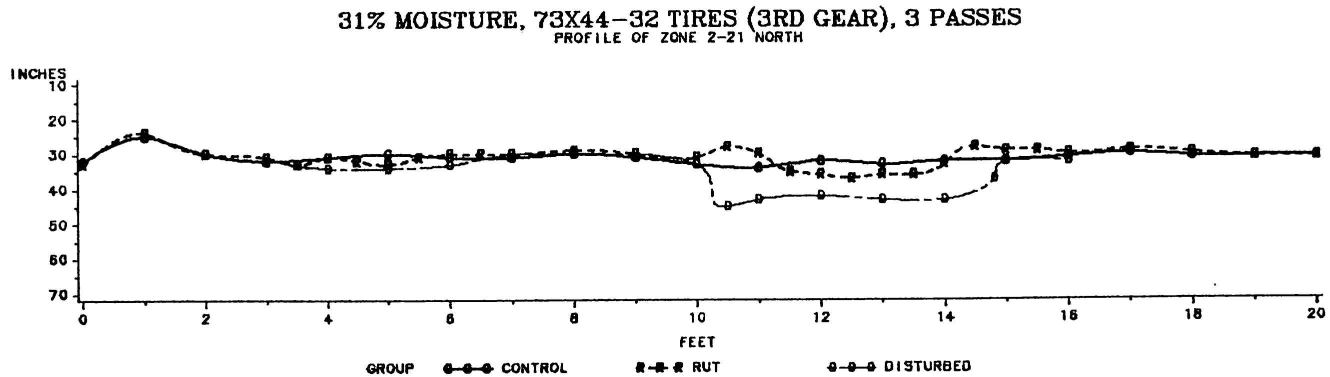


Figure 29. Example rut profiles for 2nd gear with the 73x44-32 tires at 3 passes (wet trial)



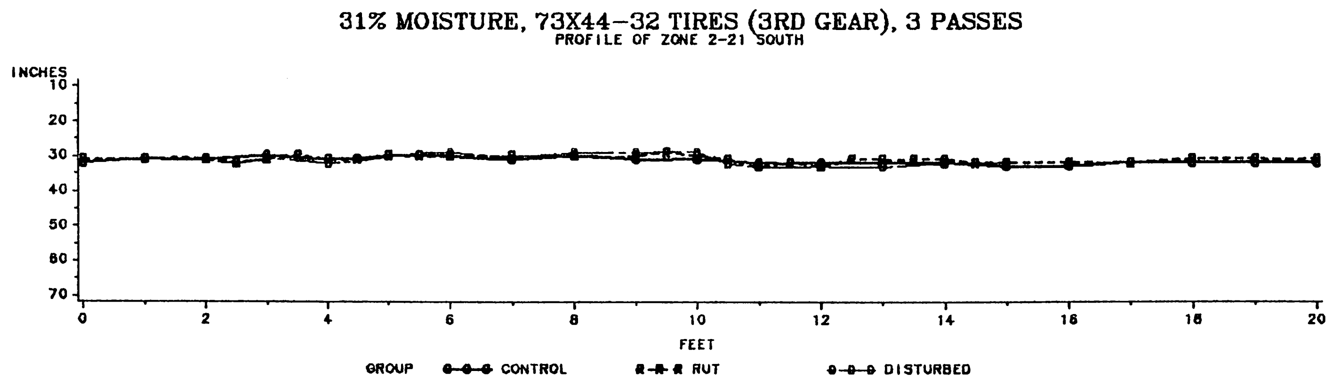


Figure 30. Example rut profiles for 3rd gear with the 73x44-32 tires at 3 passes (wet trial)

Table 32. Mean rut area by operating gear and pass (wet trial)

Pass	Mean[1] rut area (ft^2) 73x44-32 tires 2nd gear	3rd gear	Mean[3] across gear
1	0.92	0.68	0.80 (A)
3	1.37	1.17	1.27 (B)
Mean[3] across pass	1.14 (a)	0.92 (a)	

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

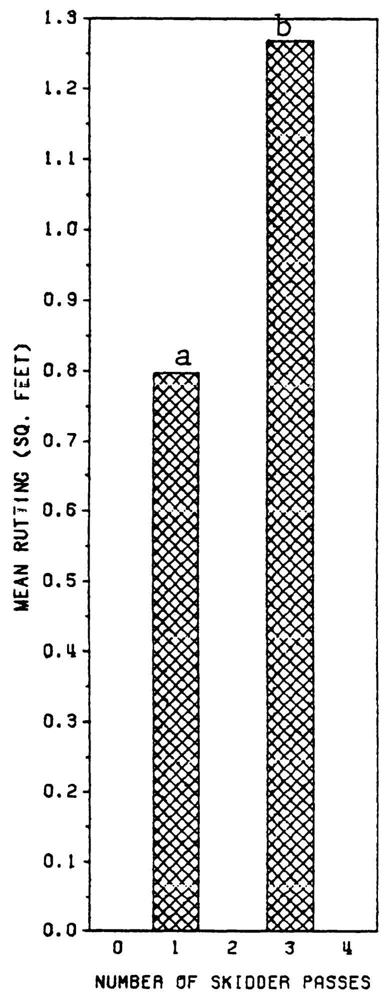


Figure 31. Mean rut area by pass (wet trial): Mean pooled across blocks and operating gears. Means with the same letter were not significantly different ($\alpha = 0.10$)

(Figure 32). The lower wheel slip with third gear operation contributed to the decrease in area of churn. The correlation between area of churn and slip was 0.58 ($p = 0.0466$).

Cone Index

Mean cone index values before and after skidding are given in Table 34. All cone index values decreased after skidding. This decrease may have been caused by the tires churning the soil, as well as a change in soil moisture conditions due to machine vibration. The skidder could have rearranged the soil/moisture matrix in a manner much similar to a vibrator used for settling concrete. The concrete vibrator makes the concrete appear "wetter" even though the moisture content has not changed. When measured on a volume basis, moisture content would be greater after vibrating as air filled pores are removed. A skidder may affect the soil in a similar manner, increasing the moisture content on a volume basis thereby decreasing cone penetrometer resistance.

Although cone index decreased after skidding, the causes of the changes from operating gear, pass, or interaction between operating gear and pass were not distinguishable (Table 35).

Tire Size and Operating Gear Comparison

The general information for comparison of tire size and operating gear is found in Table 18 and Table 27. The maximum number of passes attained by operating the skidder in second gear using the 67x34-25 tires was 6, compared to 16 and 13 for the 73x44-32 tires with second and third gear, respectively. As mentioned in the operating gear comparison, more passes may have been possible with third gear operation, but attempts to cross through the skid zones was halted when it was necessary to downshift to second gear. Second gear operation continued until the grapple had to be used to provide forward movement. The statistical analysis was made with the 67x34-25 and 73x44-32 tires in second gear and the 73x44-32 tires in third gear, at 1 and 3 passes.

Table 33. **Mean churn area by operating gear and pass (wet trial)**

	Mean[1] churn area (ft^2)		
	73x44-32 tires		
Pass	2nd gear	3rd gear	Mean[3] across gear
1	5.14	1.25	3.19 (A)
3	6.05	3.33	4.69 (A)
Mean[3] across pass	5.60 (a)	2.29 (b)	

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

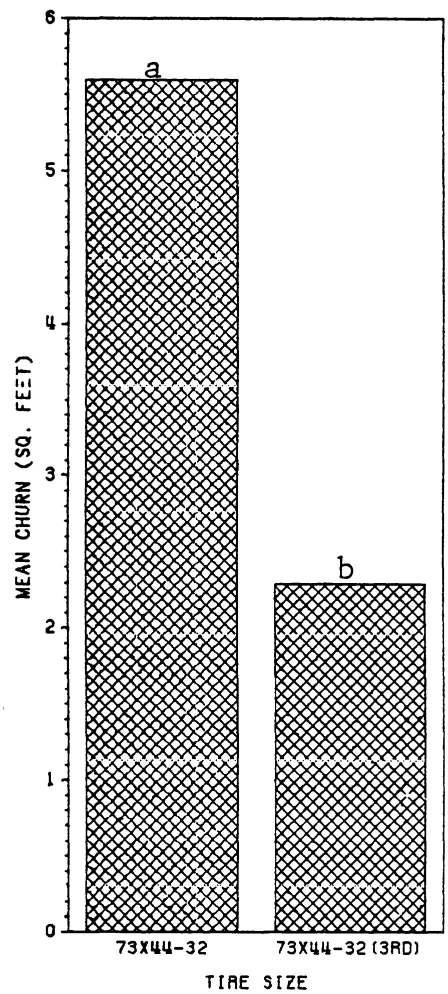


Figure 32. Mean churn area by operating gear (wet trial): Mean pooled across blocks and passes. Means with the same letter were not significantly different ($\alpha = 0.10$)

Table 34. Cone index for 2nd and 3rd gear with 73x44-32 tires at 1 and 3 passes (wet trial)

Block	Operating gear[2]	Pass	Mean[1] Cone Index (psi) Before skidding	Mean[1] Cone Index (psi) After skidding
1	2	1	109.0	40.6
	2	3	57.7	32.3
	3	1	114.6	44.8
	3	3	76.0	25.0
2	2	1	66.0	18.8
	2	3	67.1	6.5
	3	1	88.8	59.8
	3	3	90.0	17.3
3	2	1	62.9	11.0
	2	3	48.1	4.0
	3	1	54.8	25.2
	3	3	73.8	18.1

[1] Mean within each skid zone across the four sample locations
[2] With the skidder mounted with 73x44-32 tires

Table 35. Mean cone index difference by operating gear and pass (wet trial)

Pass	Mean[1] cone index difference (psi) 73x44-32 tires 2nd gear	3rd gear	Mean[2] across gear
1	-55.8	-42.8	-49.3 (A)
3	-43.4	-59.8	-51.6 (A)
Mean[2] across pass	-49.6 (a)	-51.3 (a)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

Skidder Speed

The number of passes affected the speed of the skidder (Table 36). Mean speed decreased from 340 ft/min (103.6 m/min) at pass 1, to 225 ft/min (68.6 m/min) at pass 3 (Figure 33). Speed decreased 175, 125, and 46 ft/min (53.3, 38.1, and 14.0 m/min) between 1 and 3 passes for the 67x34-25 tires (second gear), 77x44-32 (second gear), and 73x44-32 tires (third gear), respectively. Slip was a major factor contributing to the difference in speed between 1 and 3 passes. The correlation between speed and slip was -0.93 ($p = 0.0001$).

Tire Slip

Tire slip was affected by the interaction between tire size/operating gear combinations and the number of skidder passes; that is, tire slip at a given number of passes was affected by tire size/operating gear combinations (Table 37). Tire slip increased between 1 and 3 passes except for the 73x44-32 tires with third gear operation. For both tire sizes with second gear operation, slip increased dramatically between 1 and 3 passes.

Rut Profiles

Area of compaction was affected by tire size/operating gear (Table 38). Skidding with the 67x34-25 tires in second gear produced a compaction effect; there was a net loss in rut profile area (Figure 34). Operation in second and third gears with the 73x44-32 tires caused a tillage effect of -0.67 and -0.20 ft^2 (-0.06 and -0.02 m^2), respectively. These compaction and tillage effects were minimal.

Different passes for a given tire size/operating gear affected area of disturbance (Table 39). Skidding with the 67x34-25 tires in second gear at 3 passes resulted in the highest disturbance. All other

Table 36. Mean skidder speed by tire size/gear and pass (wet trial)

Pass	Mean[1] speed (ft/min)			Mean[2] across tire/gear
	Tire size/gear			
	67x34-25(2nd)	73x44-32(2nd)	73x44-32(3rd)	
1	346	332	343	340 (A)
3	171	207	297	225 (B)
Mean[2] across pass	259 (a)	269 (a)	320 (a)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

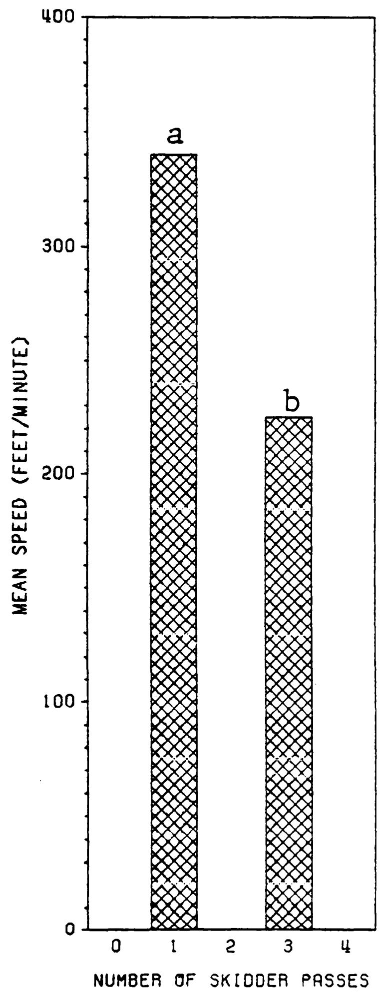


Figure 33. Mean skidder speed by pass (wet trial): Mean pooled across blocks and tire size/operating gears. Means with the same letter were not significantly different ($\alpha = 0.10$).

Table 37. Mean tire slip by tire size/gear and pass (wet trial)

	Mean[1,2] tire slip (%)		
	Tire size/gear		
Pass	67x34-25(2nd)	73x44-32(2nd)	73x44-32(3rd)
1	9.1 (b)	4.8 (b)	3.8 (b)
3	39.9 (a)	34.6 (a)	10.7 (b)

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

Table 38. **Mean compaction area by tire size/gear and pass (wet trial)**

Pass	Mean[1] compaction area (ft^2)			Mean[3] across tire/gear
	Tire size/gear			
	67x34-25(2nd)	73x44-32(2nd)	73x44-32(3rd)	
1	0.46	-0.42	-0.13	-0.03 (A)
3	0.52	-0.92	-0.27	-0.22 (A)
Mean[3] across pass	0.49 (a)	-0.67 (b)	-0.20 (b)	

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

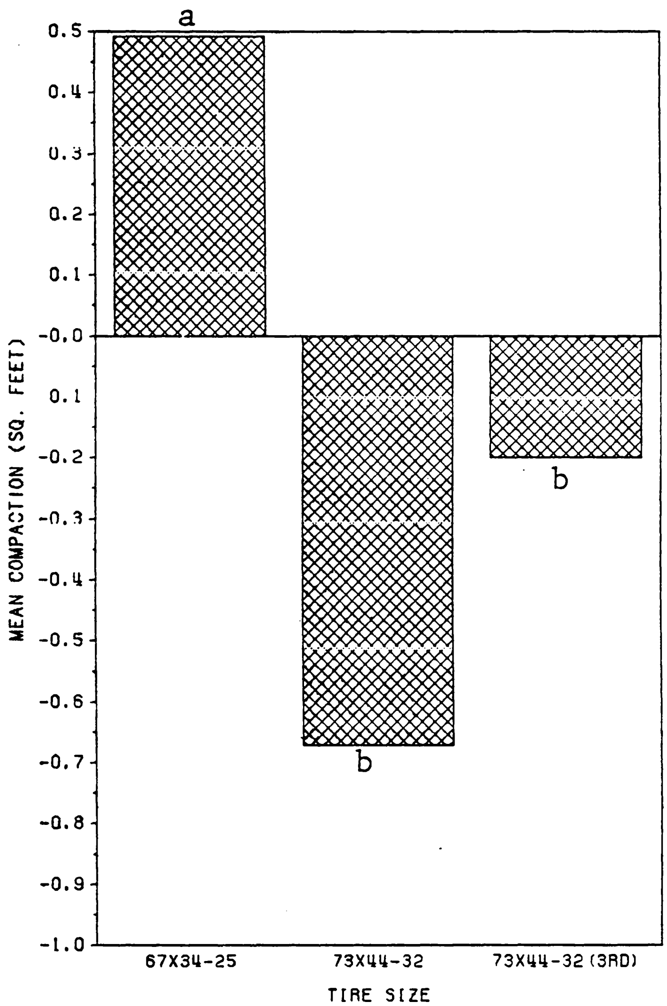


Figure 34. **Mean compaction area by tire size/operating gear (wet trial):** Mean pooled across blocks and passes. Means with the same letter were not significantly different ($\alpha = 0.10$).

disturbance values were similar, with a range of 1.12 ft^2 (0.10 m^2) for third gear operation with the 73x44-32 tires at pass 1, up to 5.14 ft^2 (0.48 m^2) for second gear operation with the 73x44-32 tires at pass 3. Tire slip influenced the amount of disturbance. High slip sheared the soil to greater depth. The correlation between disturbance and slip was 0.79 ($p = 0.0001$).

Both tire size/operating gear and the number of skidder passes affected rut area (Table 40). Mean rut area was higher with the 67x34-25 tires in second gear (Figure 35). Rut area for the 73x44-32 tires in second and third gear was similar. Mean rut area was 1.80 ft^2 (0.17 m^2) for the 67x34-25 tires and 1.14 and 0.92 ft^2 (0.11 and 0.09 m^2) for the 73x44-32 in second and third gears, respectively. Mean rut area increased from 0.92 ft^2 (0.09 m^2) at pass 1 to 1.66 ft^2 (0.15 m^2) at pass 3 (Figure 36).

Area of churned soil was affected by number of passes for a given tire size/operating gear (Table 41). Mean churn area increased from 1.82 to 9.60 ft^2 (0.17 to 0.89 m^2) with the 67x34-25 tires in second gear at 1 and 3 passes, respectively. The churn at 3 passes for the 67x34-25 tires was also greater than the churn at 1 and 3 passes with the 73x44-32 tire when the skidder was operated in third gear. Operating the skidder in second gear with the 73x44-32 tires provided little difference in the effect on area of churned soil in comparison with the 67x34-25 tires in second gear, and the 73x44-32 tires in third gear.

Cone Index

Mean cone index values are given in Table 42. All cone index values decreased after skidding and may have resulted from the churning of the soil by the tires, as well as the "concrete vibrator" effect as mentioned in the previous section.

Table 39. Mean disturbance area by tire size/gear and pass (wet trial)

	Mean[1],[3] disturbance area (ft^2)		
	Tire size/gear		
Pass	67x34-25(2nd)	73x44-32(2nd)	73x44-32(3rd)
1	2.28 (b)	4.71 (b)	1.12 (b)
3	10.12 (a)	5.14 (b)	3.01 (b)

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

Table 40. Mean rut area by tire size/gear and pass (wet trial)

Pass	Mean[1] rut area (ft^2)			Mean[3] across tire/gear
	Tire size/gear			
	67x34-25(2nd)	73x44-32(2nd)	73x44-32(3rd)	
1	1.16	0.92	0.68	0.92 (B)
3	2.44	1.37	1.17	1.66 (A)
Mean[3] across pass	1.80 (a)	1.14 (b)	0.92 (b)	

[1] Mean pooled across 3 blocks.
[3] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

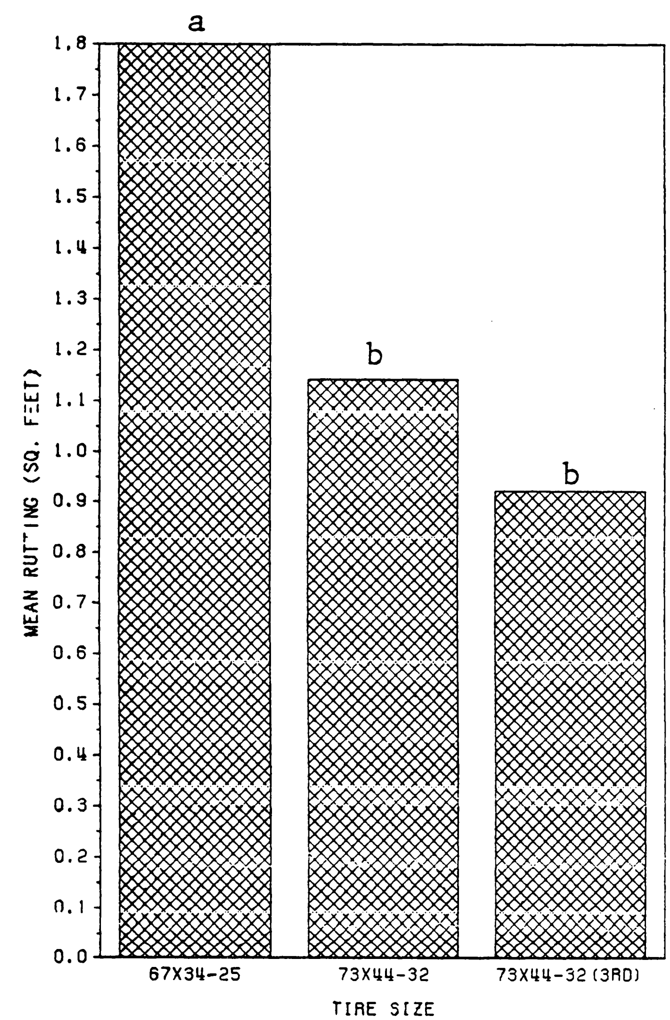


Figure 35. Mean rut area by tire size/operating gear (wet trial): Mean pooled across blocks and passes. Means with the same letter were not significantly different ($\alpha = 0.10$).

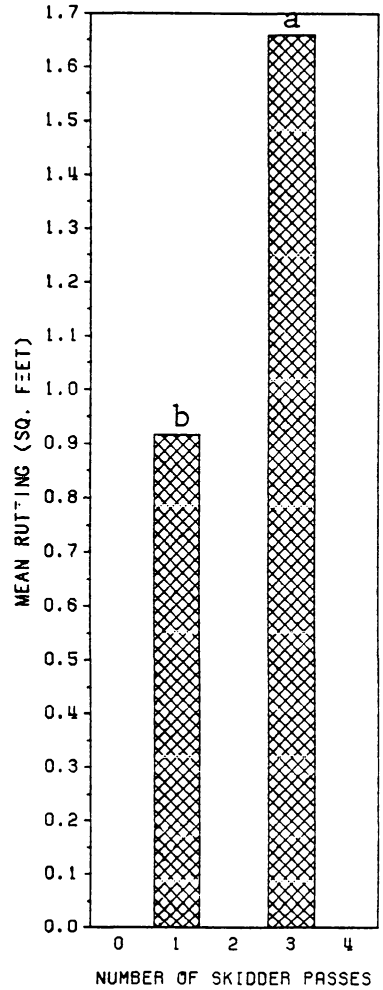


Figure 36. Mean rut area by pass (wet trial): Mean pooled across blocks and tire size/operating gears. Means with the same letter were not significantly different ($\alpha = 0.10$).

Table 41. Mean churn area by tire size/gear and pass (wet trial)

Pass	Mean[1],[3] churn area (ft^2)		
	Tire size/gear		
	67x34-25(2nd)	73x44-32(2nd)	73x44-32(3rd)
1	1.82 (bc)	5.14 (abc)	1.25 (c)
3	9.60 (a)	6.05 (ab)	3.33 (bc)

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

Table 42. Cone index for tire size and gear comparison (wet trial)

Block	Tire size/gear	Pass	Mean[1] Cone Index (psi) Before skidding	After skidding
1	67x34-25/2nd	1	48.5	13.1
	67x34-25/2nd	3	69.8	19.4
	73x44-32/2nd	1	109.0	40.6
	73x44-32/2nd	3	57.7	32.3
	73x44-32/3rd	1	114.6	44.8
	73x44-32/3rd	3	76.0	25.0
2	67x34-25/2nd	1	77.5	45.2
	67x34-25/2nd	3	69.8	11.3
	73x44-32/2nd	1	66.0	18.8
	73x44-32/2nd	3	67.1	6.5
	73x44-32/3rd	1	88.8	59.8
	73x44-32/3rd	3	90.0	17.3
3	67x34-25/2nd	1	61.7	37.7
	67x34-25/2nd	3	84.2	26.5
	73x44-32/2nd	1	62.9	11.0
	73x44-32/2nd	3	48.1	4.0
	73x44-32/3rd	1	54.8	25.2
	73x44-32/3rd	3	73.8	18.1

[1] Mean within each skid zone across the four sample locations

Difference in cone index from skidding was not affected by tire size/operating gear, pass, or interaction between tire size/operating gear and pass (Table 43). There were not any apparent trends for the decreases in cone index for each tire size/operating gear at 1 and 3 passes.

Moist vs. Wet Soil

General Description

Pre-treatment soil moisture content averaged 19.2 and 31.6% for the moist (July) and wet (September) trials, respectively. The moist trial consisted of three tire sizes (28L-26, 67x34-25, 73x44-32) at four pass levels (1, 3, 9, 27) and three replications. In one skid zone the 28L-26 tires only completed 14 of 27 passes.

The wet trial consisted of three tire/gear treatments (67x34-25(2nd gear), 73x44-32(2nd gear), 73x44-32(3rd gear)) at several pass levels. The pass levels during the wet trial were not consistent across all three tire/gear treatments, nor with the moist trial pass treatments because the high soil moisture did not allow the application of high pass levels. Sixty-seven percent of the 9 pass treatments and 100% of the 27 pass treatments were not completed during the wet trial. In three instances 9 passes were completed; twice with third gear operation using the 73x44-32 tires, and once with second gear operation using the 73x44-32 tires. The 28L-26 tires were not used during the wet (September) trial because they failed to complete 1 pass (Figure 8 on page 35).

The moist vs. wet comparison was made with the 67x34-25 and 73x44-32 tires in second gear operation at 1 and 3 passes.

Table 43. Mean cone index difference by tire size/gear and pass (wet trial)

Pass	Mean[1] cone index difference (psi)			Mean[2] across tire/gear
	Tire size/gear			
	67x34-25(2nd)	73x44-32(2nd)	73x44-32(3rd)	
1	-30.6	-55.8	-42.8	-43.1 (A)
3	-55.6	-43.4	-59.8	-52.9 (A)
Mean[2] across pass	-43.1 (a)	-49.6 (a)	-51.3 (a)	

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

Dependent Variables

Skidder Speed

There was an interaction between soil moisture content and the number of skidder passes; that is, skidder speed at a given number of passes was affected by soil moisture content (Table 44). Speed was highest for the skidder equipped with the 67x34-25 tires on moist soil, and was the result of a different axle differential ratio and higher governed engine RPM. Speed changed very little between 1 and 3 passes on moist soil (Figure 37). On wet soil, mean speed decreased from 339 to 189 ft/min (103.3 to 57.6 m/min) at 1 and 3 passes, respectively. This dramatic decrease in speed by pass at high soil moisture content was due to an increase in tire slip. With successive passes on wet soil, the ground surface deteriorated quickly which increased tire slip and reduced skidder speed.

Tire Slip

Tire slip was affected by tire size and an interaction between soil moisture and number of skidder passes (Table 45). Tire slip was higher with the 67x34-25 tires (Figure 38). Mean slip was 13 and 9% for the 67x34-25 and 73x44-32 tires, respectively. Several factors may have contributed to the higher slip with the 67x34-25 tires. During the moist soil trial the 67x34-25 tires were worn and had rounded cleats, which could have reduced their pull capability. In addition, tires with a larger footprint area, such as the 73x44-32 tires, have higher pull capabilities. Since the load weights were kept as uniform as possible, the pull effort with the 73x44-32 tires was lower, and hence the tire slip.

Pass did not affect slip on moist soil, but had a considerable affect with the wet soil condition (Figure 39). Mean slip at 1 and 3 passes on wet soil was higher than the slip which occurred on moist soil. Mean slip increased from 7% at pass 1 to 37% at pass 3 on wet soil conditions.

Table 44. Mean skidder speed by tire size and pass

Pass	Mean[1] speed (ft/min)			
	Soil moisture content and tire size			
	Moist		Wet	
	67x34-25	73x44-32	67x34-25	73x44-32
1	427	335	346	332
3	408	381	171	207

[1] Mean pooled across 3 blocks.

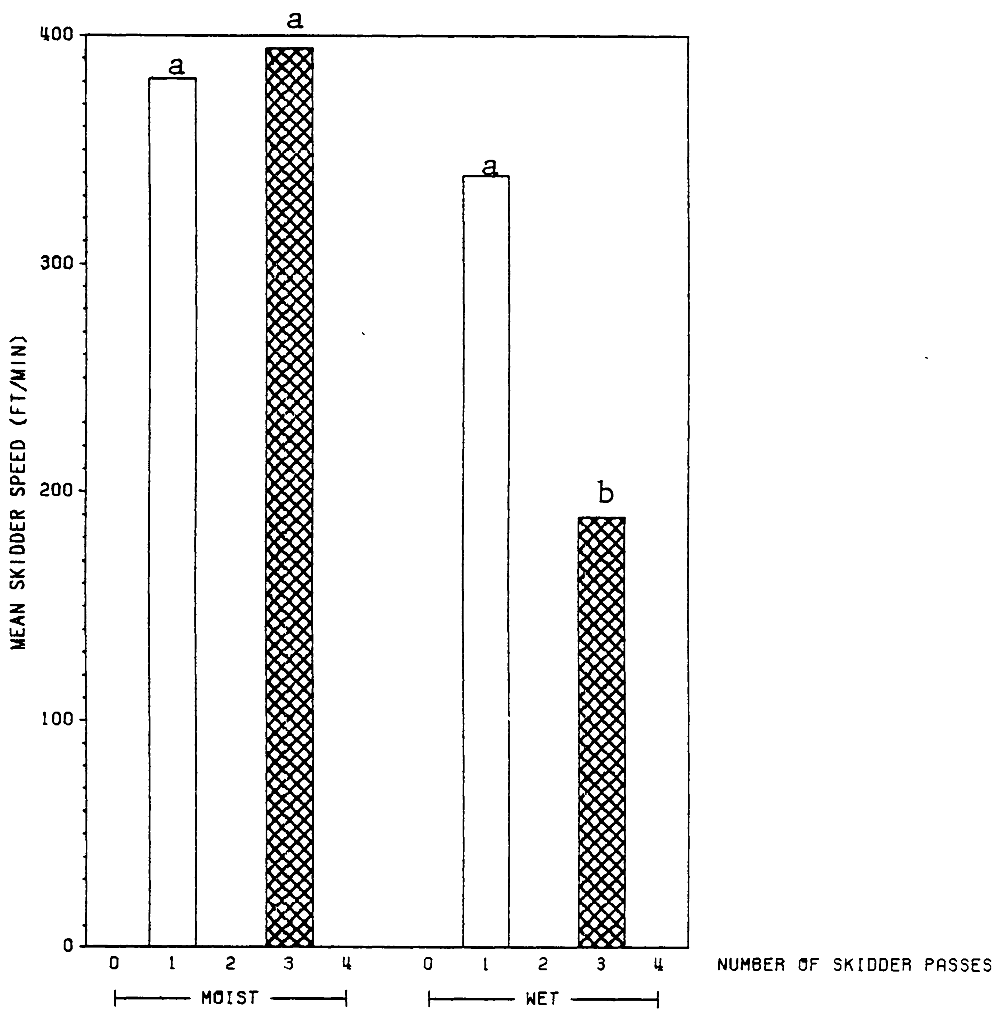


Figure 37. Mean skidder speed by pass (moist vs. wet soil conditions): Mean pooled across blocks and tire sizes. Means with the same letter were not significantly different ($\alpha = 0.10$).

Table 45. Mean tire slip by tire size and pass

	Mean[1] tire slip (%)			
	Soil moisture condition and tire size			
	Moist		Wet	
Pass	67x34-25	73x44-32	67x34-25	73x44-32
1	1.0	-2.3	9.1	4.8
3	2.0	-0.7	39.9	34.6

[1] Mean pooled across 3 blocks.

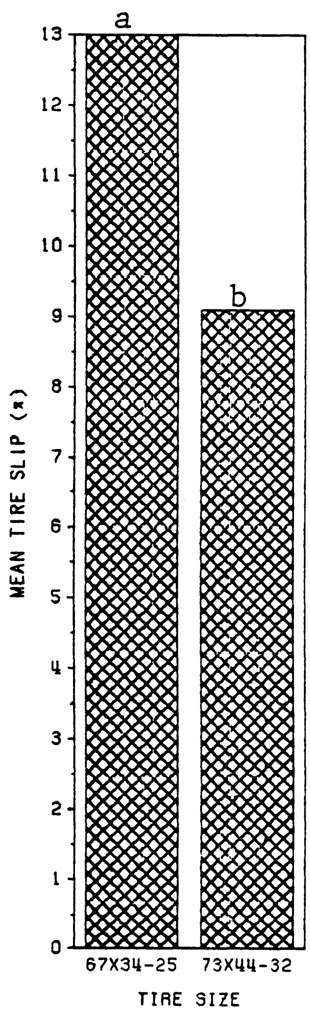


Figure 38. Mean tire slip by tire size: Mean pooled across blocks, soil moisture, and passes. Means with the same letter were not significantly different ($\alpha = 0.10$).

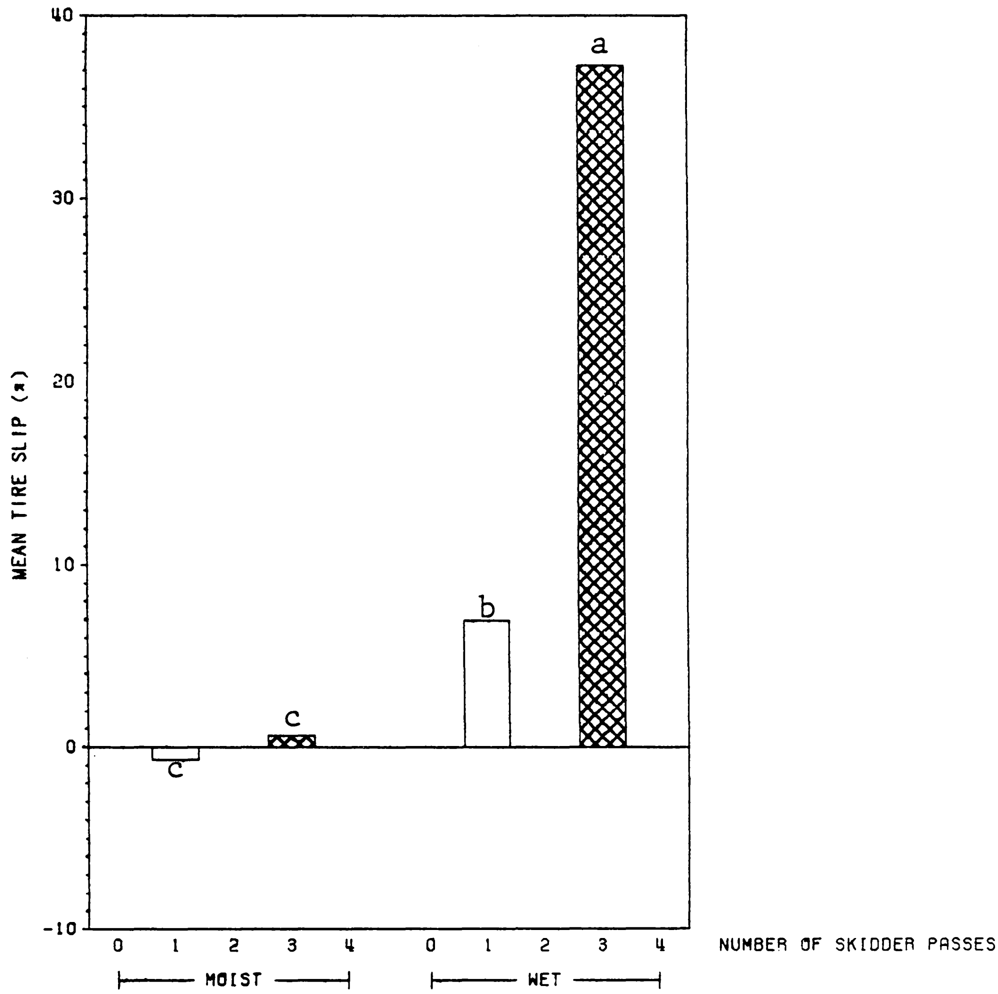


Figure 39. Mean tire slip by pass (moist vs. wet soil conditions): Mean pooled across blocks and tire sizes. Means with the same letter were not significantly different ($\alpha = 0.10$).

Rut Profiles

Since the rut and churn variables did not apply to the moist soil trial, comparisons with these variables were not included in this section.

Compaction area was affected by an interaction between soil moisture content and tire size (Table 46). At both soil moisture contents the 73x44-32 tires produced a tillage effect; a negative compaction value. This tillage effect for the 73x44-32 tires between the moist and wet soil conditions was similar (Figure 40). The compaction effect was much different with the 67x34-25 tires for the moist and wet conditions. Under moist soil conditions, the 67x34-25 tires produced a small tillage effect. But when the soil was wet, the 67x34-25 tires produced a compaction effect of 0.49 ft^2 (0.05 m^2) across 1 and 3 passes. The condition of the 67x34-25 tires and difference in skidders across the two soil moisture content trials may have contributed to this difference. The torque output of the skidders along with the tire cleat geometry may have been crucial to soil movement as measured by the compaction variable.

Disturbance area was affected by an interaction between soil moisture, tire size, and the number of skidder passes; that is, disturbance area for a given number of passes for a given tire size was affected by soil moisture condition (Table 47). Mean disturbance area was similar for the 67x34-25 and 73x44-32 tires at 1 and 3 passes on moist soil. Disturbance with the 67x34-25 tires at pass 1 on wet soil was not greater than disturbance on moist soil. But, by pass 3, disturbance increased rapidly to 10.12 ft^2 (0.94 m^2) with the 67x34-25 tires. This high disturbance was the result of deep rutting. The 73x44-32 tires had a higher disturbance at pass 1 on wet soil than disturbance at 1 and 3 passes with both tires on moist soil. This disturbance was not greater than that caused by the 67x34-25 tires at pass 1 on moist soil. At pass 3, disturbance did not increase with the 73x44-32 tires on wet soil conditions.

Table 46. Mean compaction area by tire size and pass

	Mean[1] compaction area (ft^2)			
	Soil moisture condition and tire size			
	Moist		Wet	
Pass	67x34-25	73x44-32	67x34-25	73x44-32
1	-0.07	-0.35	0.46	-0.42
3	-0.07	-0.07	0.52	-0.92

[1] Mean pooled across 3 blocks.

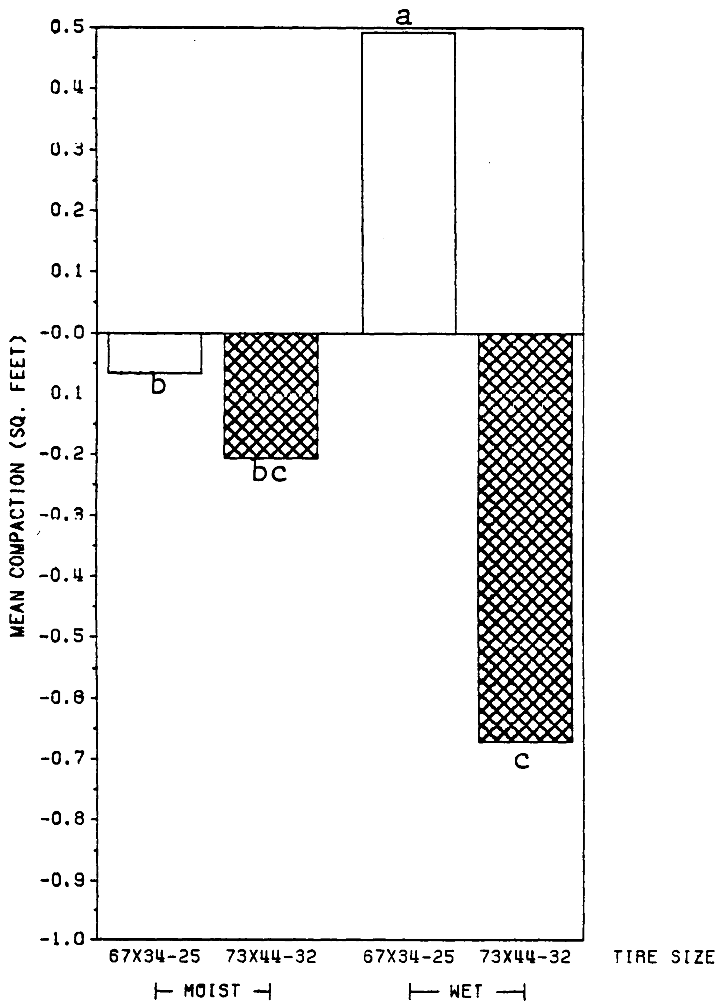


Figure 40. **Mean compaction area by tire size (moist vs. wet soil condition):** Mean pooled across blocks and passes. Means with the same letter were not significantly different ($\alpha = 0.10$).

Table 47. Mean disturbance area by tire size and pass

	Mean[1] [2] disturbance (ft^2)			
	Soil moisture condition and tire size			
	Moist		Wet	
Pass	67x34-25	73x44-32	67x34-25	73x44-32
1	0.88 (c)	0.80 (c)	2.28 (bc)	4.71 (b)
3	0.73 (c)	0.37 (c)	10.12 (a)	5.14 (b)

[1] Mean pooled across 3 blocks.
[2] Means with the same letter were not significantly different with Duncan's multiple range test ($\alpha = 0.10$).

Figure 41 and Figure 42 show the dramatic effect of soil moisture condition on rutting at 3 passes for the 67x34-25 and 73x44-32 tires. It was clearly evident that rutting was much less when operating on moist soil conditions.

Cone Index

Cone index before and after skidding for moist and wet soil conditions by block and treatment combination are given in Table 48. Wet soil conditions allowed greater mixing of the soil, which resulted in decreased penetration resistance.

Difference in cone index was affected by an interaction between tire and pass, and an interaction between soil moisture and tire size (Table 49). Cone index decreased after skidding for both tire sizes at 1 and 3 passes, except for pass 3 with the 73x44-32 tires on moist soil. On moist soil, mean difference in cone index across passes 1 and 3 was -31 psi (-213.7 kPa) for the 67x34-25 tires, and -5 psi (-34.5 kPa) for the 73x44-32 tires (Figure 43). On wet soil, mean difference in cone index across passes 1 and 3 for the 67x34-25 and 73x44-32 tires was similar to the mean value with the 67x34-25 tires on moist soil. It was possible that pre-treatment soil moisture differences between the tire sizes during the moist soil trial caused this interaction. Pre-treatment soil moisture content at 1 and 3 passes during the moist soil trial averaged 20.5 and 15.7% for the skid zones which received the 67x34-25 and 73x44-32 tire treatments, respectively. The corresponding pre-treatment soil moisture contents during the wet trial were 31.4 and 31.3%. The correlation between pre-treatment soil moisture content and difference in cone index was -0.67 ($p = 0.0003$).

The effect of the number of skidder passes on difference in cone index for the two tire sizes is displayed in Figure 44. The range in cone index means across blocks between the soil moisture contents at each pass level was much smaller for the 67x34-25 tires. The range was 16.5 and 7.8 psi (113.8 and 53.8 kPa) for the 67x34-25 tires at 1 and 3 passes, respectively. This indicated that

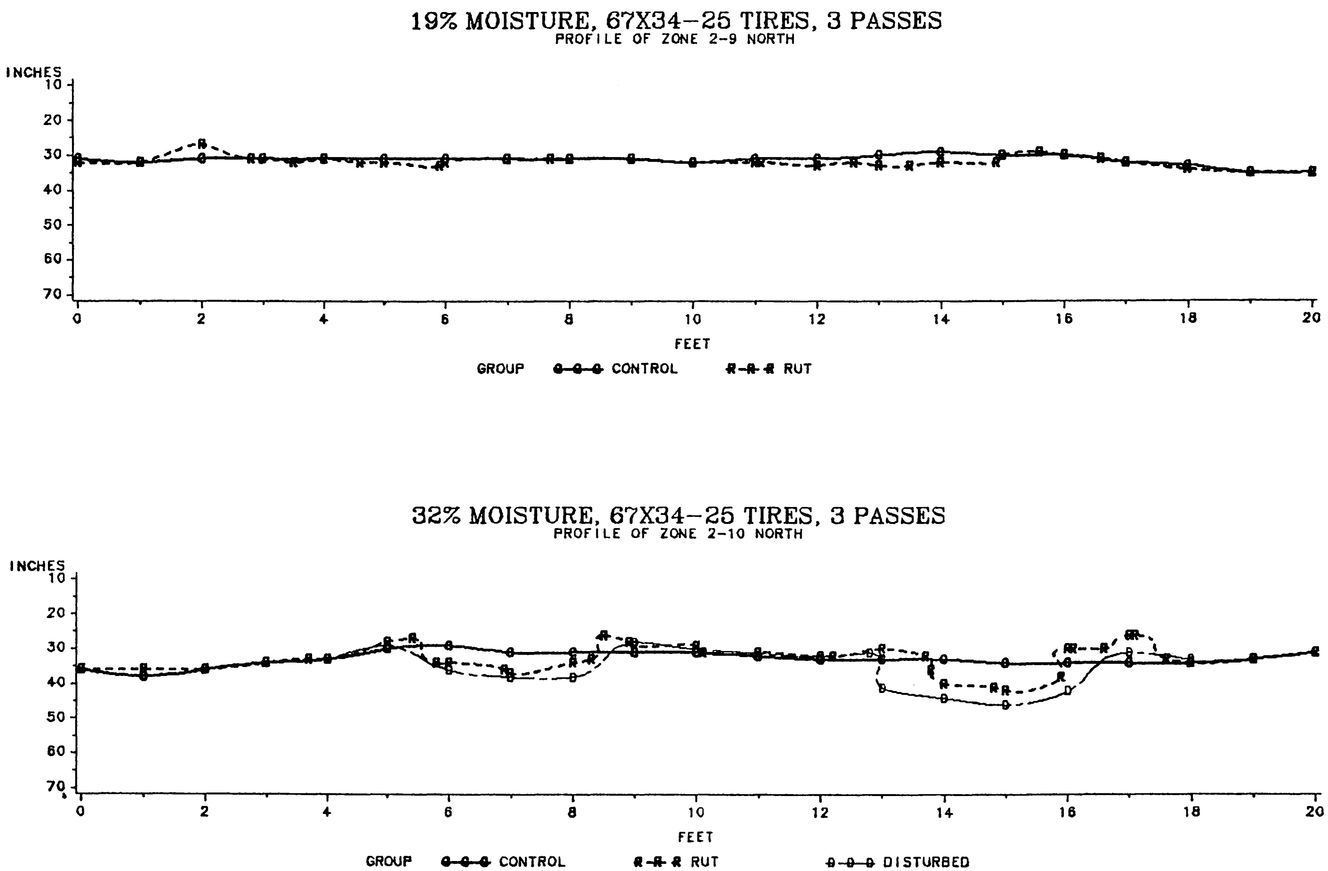


Figure 41. Example rut profiles for the 67x34-25 tires at 3 passes (moist vs. wet soil conditions)

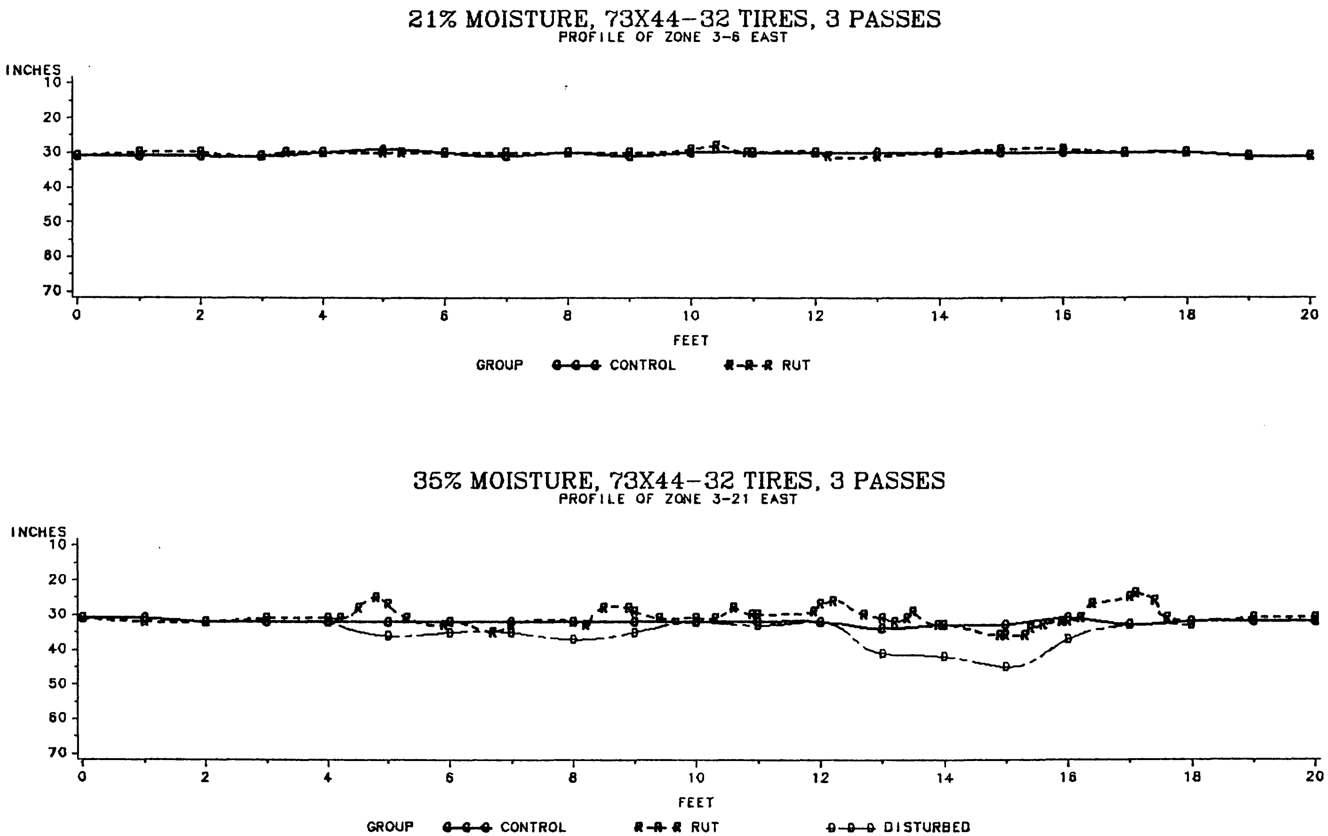


Figure 42. Example rut profiles for the 73x44-32 tires at 3 passes (moist vs. wet soil conditions)

Table 48. Cone index before and after skidding (moist vs. wet soil)

Soil Moisture	Block	Tire size	Pass	Mean[1] Cone Index (psi) Before skidding	After skidding
Moist	1	67x34-25	1	190.0	181.5
		67x34-25	3	110.2	50.0
		73x44-32	1	298.5	278.3
		73x44-32	3	289.0	310.6
	2	67x34-25	1	226.0	198.3
		67x34-25	3	158.1	143.5
		73x44-32	1	135.2	123.5
		73x44-32	3	212.5	211.5
	3	67x34-25	1	105.8	99.8
		67x34-25	3	113.3	44.6
		73x44-32	1	126.7	111.3
		73x44-32	3	129.4	124.6
Wet	1	67x34-25	1	48.5	13.1
		67x34-25	3	69.8	19.4
		73x44-32	1	109.0	40.6
		73x44-32	3	57.7	32.3
	2	67x34-25	1	77.5	45.2
		67x34-25	3	69.8	11.3
		73x44-32	1	66.0	18.8
		73x44-32	3	67.1	6.5
	3	67x34-25	1	61.7	37.7
		67x34-25	3	84.2	26.5
		73x44-32	1	62.9	11.0
		73x44-32	3	48.1	4.0

[1] Mean within each skid zone across the four sample locations

Table 49. Mean cone index difference by tire size and pass

	Mean[1] cone index difference (psi)			
	Soil moisture condition and tire size			
	Moist		Wet	
Pass	67x34-25	73x44-32	67x34-25	73x44-32
1	-14.1	-15.8	-30.6	-55.8
3	-47.8	5.3	-55.6	-43.4

[1] Mean pooled across 3 blocks.

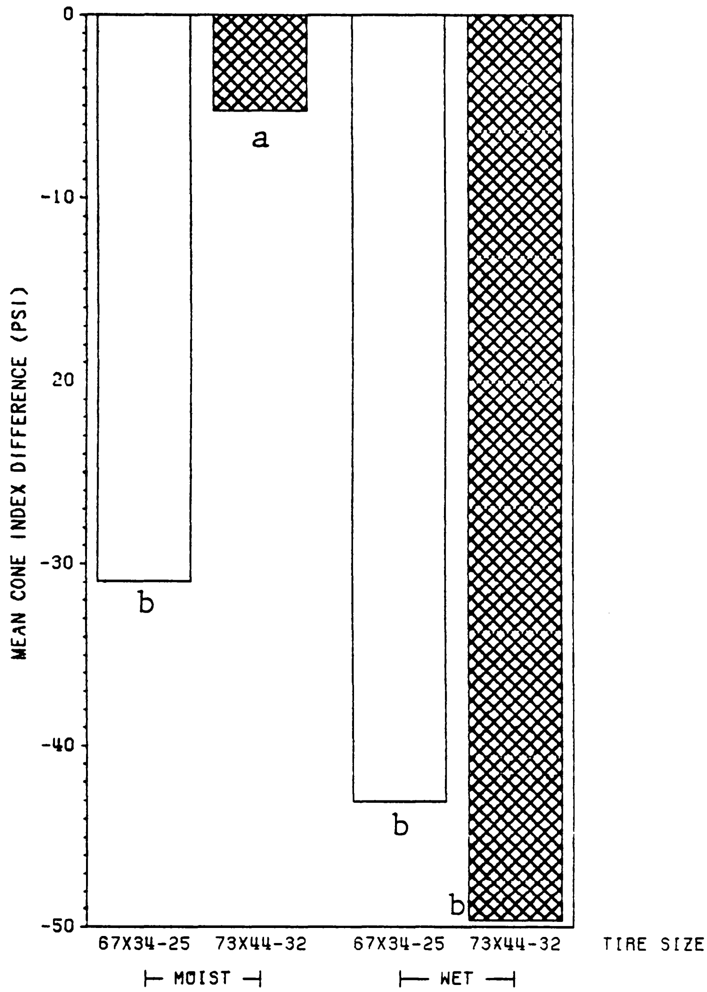


Figure 43. Mean cone index difference by tire size (moist vs. wet soil conditions): Mean pooled across blocks and passes. Means with the same letter were not significantly different ($\alpha = 0.10$).

the effect on differences in cone index for the 67x34-25 tires was more pronounced than that of the 73x44-32 tires.

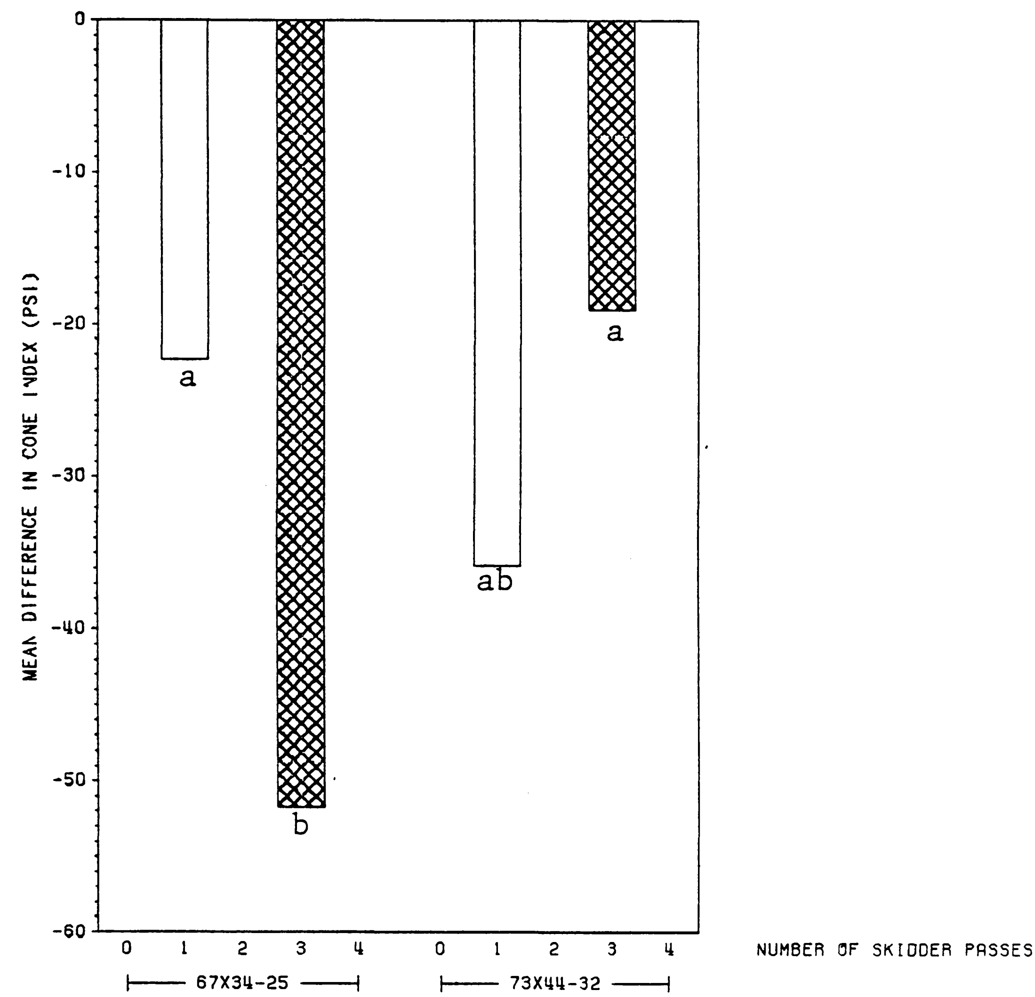


Figure 44. Mean cone index difference by pass and tire size: Mean pooled across blocks and soil moisture. Means with the same letter were not significantly different ($\alpha = 0.10$).

Management Implications

The forest manager and harvest planner must take all site factors into account before laying out a harvest operation. For the area on which this study occurred, the goal should generally not be to minimize the total area affected by harvesting, but to minimize the overall impact across the site under present and future management objectives and operations, while meeting wood flow constraints.

On moist soil the benefits of tire selection were not evident, but limiting the number of skidder passes over a particular area may prove beneficial in terms of soil effects. Concentrating skidding on skid trails where more than nine passes occur may decrease the ability of the soil under the skid trail to allow water movement or permit normal tree growth. As suggested by Batardy and Abeels (1985), lowering the soils ability to allow water movement may create a "damming effect". Obviously this effect will depend on the depth to which subsurface flow has been affected, or the presence of water flow restricting soil layers.

Exceeding nine skidder passes on moist soil may also decrease non-capillary pore space to less than 10%, the level considered critical to tree growth (Terry and Campbell 1981). Although the difference in soil bulk density was affected little after nine passes, the economic and biological impact were not known. Therefore, dispersing skidder traffic, as is commonly done, would result in the least impact on the site. Skidder performance was not appreciably affected by the number of skidder passes, nor by tire size, when operating on moist soil.

With wet soil conditions, the wider tires proved beneficial to skidder performance and reduced adverse impact on the site. Operability was maintained with the 73x44-32 tires and rutting was less. The number of skidder passes was very important to skidder performance and rut formation. By three passes tire slip and rutting had increased dramatically.

Reduction of wheel slip by operating in third gear and adjusting engine RPM was also beneficial on wet conditions. The benefits of reduced wheel slip were quite apparent; skidder speed was not affected while rut formation was reduced. To maintain skidder operation, as well as minimize the effect of skidding on the site, the wide tires, reduced wheel torque, and dispersed skidding are suggested.

A particular point of interest that is probably well known to harvesting personnel but not explicitly stated in research literature, is that the benefits attained through operating strategies or tire selection also benefit the condition of the site during and after harvesting. This was clearly evident during the wet soil trial; operational guides such as operating in third gear to limit slip, or selecting wider tires, also benefitted the condition of the site.

The different methods by which the test blocks and the area surrounding the blocks were harvested led to an interesting difference in skidder trafficability on these areas with wet soil conditions. The area surrounding the blocks was conventionally harvested with a feller-buncher and grapple skidder, while the trees on the test blocks were chain-saw felled and cable-yarded to maintain "undisturbed" conditions. Both were harvested together when soil moisture content was low ($\cong$ 15 to 20%).

Under wet soil conditions the conventionally harvested area withstood trafficking when operating the loaded skidder, whereas the "undisturbed" blocks quickly deteriorated and became deeply rutted. Several factors may have contributed to this effect. The feller-buncher and grapple skidder may have compacted the soil in such a manner that an increase in moisture content did not alter the bearing capacity. In addition, conventional harvesting removed much of the litter layer material and may have allowed the top few inches of soil to dry. This would be analogous to a mulch layer in which the mulch material prevents evaporation. It was likely that both conditions were present on the conventionally harvested area.

This trafficability effect may prove worthy for operations. For example, by installing skid trails with a feller-buncher and grapple skidder during "dry" to "moist" soil conditions, the trails may provide a means to log the site after soil moisture increases. Once the prepared skid trails are installed, the site may be logged at any convenient time.

During the "dry" season, several crews may be utilized to log skid trails on sites designated for harvest during the "wet" season. All other logging crews would be assigned to operable sites; those sites which do not require specialized equipment and considerable effort to log productively.

During the "wet" season all crews would be assigned to sites which are still operable, and those sites which have the prepared skid trails. It should be understood that skidder traffic patterns on operable sites and prepared skid trail sites would be different; skidder traffic would be dispersed on operable sites and concentrated on the prepared skid trail sites. This would appear to contradict the previous recommendation of dispersing skidder traffic on wet sites. As mentioned earlier, the main objective should be to maintain operations while minimizing the overall impact across the site under present and future management objectives and operations. Those sites which became "wet" and could not be logged when "dry" due to scheduling problems or the need for wood, would be in a better condition following harvest through the use of the prepared skid trails. One must remember that wood must be supplied to the mill, and, at times, the best conditions for logging are not present. The prepared skid trail system may decrease the impact of harvesting on sites logged when conditions are not favorable, as well as maintain productivity and provide more flexible harvest scheduling. It is further suggested that logging slash be spread over the prepared skid trails once harvesting begins to provide additional bearing capacity (King and Haines 1979, Bryan et al. 1985).

Further information concerning the difference in trafficability between the test blocks and the conventionally harvested area, as well as operational trials, are necessary to further investigate this phenomenon.

Summary and Conclusions

The purpose of this research project was to determine the effects of tire size, operating gear, and the number of skidder passes on skidder performance and differences in soil/site characteristics from tree-length skidding with a rubber-tired skidder. Skidder speed, tire slip, soil bulk density, soil pore space, soil saturated hydraulic conductivity, and rut formation, were measured before and after skidding.

A 29-yr-old slash pine plantation on the Lower Coastal Plain of Georgia was selected. The soils were characterized by a shallow water table during part of the year, an argillic horizon, and flat topography. Surface soil textures were sandy loam and loamy sand. Three "undisturbed" areas were prepared by chain-saw felling and cable yarding. The study was conducted with a Franklin 170 grapple skidder with three different tire sizes and four different levels of passes, under two soil moisture conditions. The two soil moisture conditions were selected to represent 1) maximum compaction ($\cong$20 to 22% moisture content), and 2) maximum puddling and rutting ($\cong$30% moisture content).

The first half of the study was conducted during July of 1986 when soil moisture on the site averaged 19.2%. The treatments consisted of all possible combinations of the three tire sizes (28L-26, 67x34-25, and 73x44-32) and four pass levels (1, 3, 9, and 27).

The effects resulting from the three tire sizes were similar. Skidder speed, soil bulk density, non-capillary pore space, saturated hydraulic conductivity, and rutting were not influenced by the different tire sizes. Tire slip for the 67x34-25 tires was higher than the 28L-26 and 73x44-32 tires, although the differences were small. Mean slip with the 67x34-25 tires was only 3.8%. The higher slip with the 67x34-25 tires may have resulted from their worn condition, or the fact that a different skidder was used. The skidder on which the 67x34-25 tires were operated had a higher governed engine RPM and different axle differential ratio than the skidder on which the 28L-26 and 73x44-32 tires were used. Speed for the skidder with the 67x34-25 tires was also higher, but after adjusting the speed for governed engine RPM and axle differential ratio the speeds were similar to those for the other tire sizes.

Tire size influenced differences in cone index from skidding, but the results were very difficult to assess. Cone index does not appear to be a good indicator of soil effects from skidding.

With moist soil conditions the major influencing factor on soil properties was the number of skidder passes. The number of passes did not have a significant affect on skidder performance; that is, tire slip and skidder speed were affected very little by the number of passes the skidder made through the test zones. Tire slip did increase with the number of passes, but not to a great amount; mean tire slip at 27 passes was only 3.4%.

The difference in soil bulk density before and after skidding increased with the number of passes. The increase was sharp up to 9 passes and then levelled off. The economic and biological implications of the increase in bulk density were not determined.

Non-capillary pore space decreased with pass for moist soil conditions. One pass had little effect whereas the effect from 3, 9, and 27 passes was greater. Non-capillary porosity less than 10% has been considered detrimental to tree growth (Terry and Campbell 1981) and therefore it is recommended that not more than 9 passes be made over the soil if ameliorative site preparation will not be undertaken.

Water drainage is of primary importance for the site on which the study occurred. Adequate drainage is essential to future management operations such as site preparation, especially since the transpirational capacity of the trees no longer exists. Subsurface water drainage may become restricted under areas where more than 9 skidder passes occur.

Common logging practice for the area in which the study occurred has been to disperse skidding over the site. This practice is one which also provides the most suitable conditions after logging when the tract is logged in a "moist" state since much of the area does not receive more than 9 passes by the skidder.

The second half of the study was conducted during September of 1986 when soil moisture averaged 31.6%. The treatments were not consistent with the moist trial, nor across pass treatments due to deep rutting which immobilized the skidder. In addition, the 28L-26 tires were inoperable as they failed to complete one pass. A different operating strategy which consisted of operating the skidder in third gear with the 73x44-32 tires was substituted for the skid zones assigned to the 28L-26 tire treatment.

The skidder was able to complete more passes when mounted with the 73x44-32 tires than with the 67x34x25 tires, but this result may have been complicated by the slightly higher water table during operation with the 67x34x25 tires. In comparison of second versus third gear while operating the 73x44-32 tires, third gear appeared to have provided the potential to extend operations. During third gear operation the skidder completed a total of 62 passes, while with second gear the skidder completed 63 passes. But, it is important to note that the stopping rules were different; with second gear the skidder continued until the grapple had to be used to provide forward movement, whereas with the third gear, the skidder was operated until it was necessary to downshift to second gear. As such, the skidder could have continued operation after downshifting to second gear until the grapple had to be used.

The principle benefits of operating in third gear was the reduced rutting. During third gear operating the skidder operator reduced engine RPM to maintain speeds similar to that with second gear, and also adjusted engine RPM at his discretion to minimize wheel slip. By three passes wheel slip with third gear was 11%, compared to 35% with second gear. With the lower wheel slip during third gear operation, rut disturbance was only 40% of that with second gear operation. Consequently, the skidder tended to operate on the litter and soil surface with third gear operation, rather than shear downward into the soil profile.

The effect of the 67x34-25 tires in second gear on rut formation was greater than that of the second gear with the 73x44x32 tires. Rut disturbance was 10.12 ft^2 (0.94 m^2) at pass 3 with the 67x34x25 tires in second gear, compared to 5.14 ft^2 (0.48 m^2) with the 73x44-32 tires in second gear.

The number of skidder passes was very important to both skidder performance and effects of rutting. With second gear operation, mean skidder speed across tires decreased from 339 ft/min (103.3 m/min) at pass 1 to 189 ft/min (57.6 m/min) at pass 3. With third gear operation, speed only decreased from 343 ft/min (104.6 m/min) at pass 1 to 297 ft/min (90.5 m/min) at pass 3. The primary reason for the higher speeds at pass 3 with third gear operation was the lower slip and the less churned soil under the tires. This fact alone encourages the dispersal of skidding. Concentrating the passes on wet soil quickly deteriorates the condition of the soil, reducing skidder speed as a result of increased tire slip.

Cone index decreased after skidding in all cases on wet soil, but the results were very difficult to assess as there were no apparent trends for the decreases. One possible mechanism involved in the decrease in cone index is that the vibrational impact of the skidder may have displaced the air filled pores with water. As such, the moisture content increases on a volume basis but remains the same on a weight basis. This increase in moisture content on a volume basis may have provided additional lubrication between the soil particles and cone penetrometer, thereby reducing penetration resistance.

While conducting the wet trial, a vast difference in bearing capacity between the test blocks and area surrounding the blocks was noticed. The area surrounding the blocks was conventionally harvested with a feller-buncher and grapple skidder, and may have "compacted" the soil in such a manner as to increase its strength even after soil moisture increased considerably. On many occasions the skidder could barely operate through the test zone, but had no difficulty once it reached the conventionally harvested area. Although this phenomenon requires additional investigation, it appears worthy of operational testing. For instance, installing prepared skid trails on a tract during "dry" to "moist" conditions may permit harvesting even after soil moisture increases considerably. Rutting potential may then actually be reduced by concentrating skidding on the prepared trails.

The greatest effect during the study was due to soil moisture. Skidder performance was not hindered while operating on moist soil, but on wet soil performance was reduced. Tire slip inceased quickly with successive passes, deep ruts were formed, and the skidder had to articulate and use its grapple to maintain forward movement.

From operational and biological standpoints, it is best to harvest during dry to moist conditions - but this is not always possible. Wood must be supplied to the mill during all types of conditions. Several suggestions to maintain wood flow while minimizing logging disturbance are:

1. Disperse skidding over the entire site with "dry" to "moist" conditions to avoid soil conditions potentially limiting to future operations. For instance, skidder passes in excess of 9 may decrease the subsurface water drainage potential of the soil thereby creating a situation where the site will require longer periods to dry. This may cause problems when scheduling site preparation.

2. Disperse skidding over the entire site with "wet" conditions to minimize deep soil rutting and maintain skidder productivity. This is already common practice for the vicinity in which the study occurred.

3. Utilize skid trails prepared during "dry" to "moist" conditions as these trails may maintain higher bearing capacity when soil moisture increases considerably. The major benefit of prepared skidder trails is the flexibility offered for harvest scheduling.

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Appendix A. Glossary

Bulk density The mass of dry soil per unit bulk volume. The bulk volume was determined before drying to constant weight at 105°C.

Capillary pore space

The pore space within a mass of soil which will hold water by capillary action; water that will not drain when submitted to 50cm of tension (0.05 atmospheres). Also called micro-pore space and "small" pore space. Given as proportion of volume of capillary pores to bulk soil volume.

Churn A rut measurement variable which represented the total area of sheared soil across one rut profile. It was the area of soil from the surface of the rut down to the point at which the tires had sheared the soil, plus the area of sheared soil which had been deposited above the control soil surface. The churn measurement variable did not apply to the moist (July) trial. See Figure 45.

Compaction A rut measurement variable which represented the difference between the area of the visual rut and the area of soil deposited above the control soil surface across one rut profile. If compaction was zero, then the area of visual rut and area of soil displaced above the control soil surface were equal (no compaction). If the value was positive, then the area of the visual rut was greater than the area of soil deposited above the control soil surface. A positive value indicated either soil compaction with or without soil displacement, or soil translocation parallel to machine travel creating a rut. If the value was negative, then the area of the visual rut was less than the area of soil deposited above the control soil surface; soil had either been deposited on top of the control soil surface without a rut being formed, or a tillage effect occurred. See Figure 45.

Disturbance A rut measurement variable which represented the area of downward rutting from the control soil surface across one rut profile. This variable was identical to the "RUT" variable for the moist (July) trial. See Figure 45.

Non-capillary pore space

The pore space within a mass of soil which when filled with water will drain when submitted to 50cm of tension (0.05 atmospheres). Also called macro-pore space or "large" pore space. Given as proportion of non-capillary pore volume to bulk soil volume.

Rut A rut measurement variable which represented the area of the visual rut across one rut profile. It was the rut which existed on the soil surface after skidding. This measurement was identical to the "DISTURBANCE" variable for the moist (July) trial. See Figure 45.

Saturated Hydraulic Conductivity

The ability of a saturated soil to allow water to flow through itself under a potential gradiant. The inverse of the resistance of a soil to water flow.

Total Pore Space

The total volume of pores in a given bulk volume of soil. The sum of capillary and non-capillary pore space.

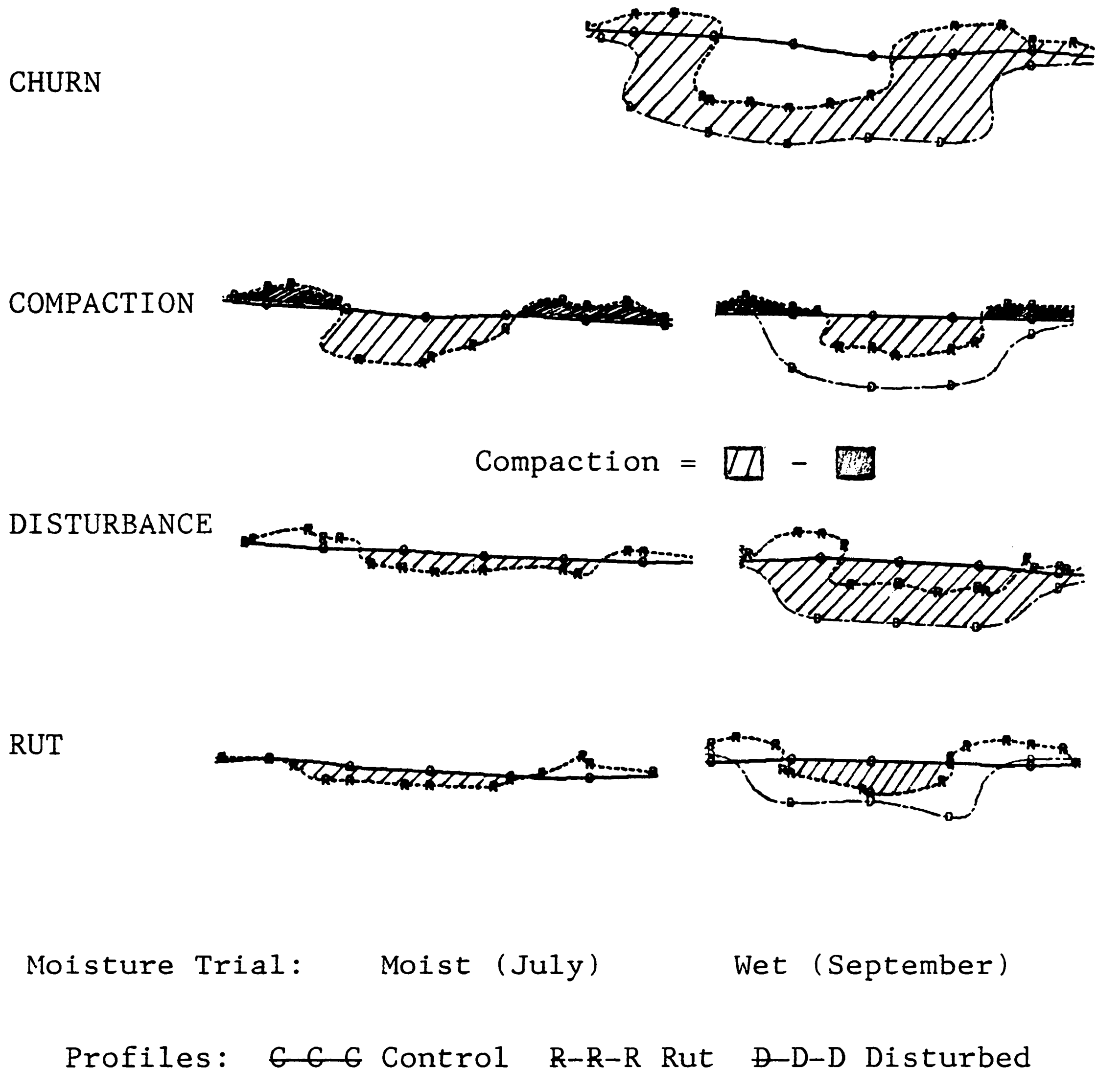

Figure 45. Rut measurement definition diagram.

Appendix B. Treatment Combinations by Block

Table 50. Block 1 treatments

Moisture Treatment	Tire Size	Passes	Operating Gear	Zone[1]
Moist (July)	28L-26	1	2	22
	28L-26	3	2	12
	28L-26	9	2	8
	28L-26	14	2	13
	67x34-25	1	2	21
	67x34-25	3	2	17
	67x34-25	9	2	14
	67x34-25	27	2	1
	73x44-32	1	2	11
	73x44-32	3	2	9
	73x44-32	9	2	19
	73x44-32	27	2	15
Wet (September)	67x34-25	1	2	3
	67x34-25	2	2	18
	67x34-25	3	2	2
	67x34-25	3	2	20
	73x44-32	1	2	23
	73x44-32	3	2	6
	73x44-32	6	2	4
	73x44-32	8	2	5
	73x44-32	1	3	24
	73x44-32	3	3	7
	73x44-32	3	3	16
	73x44-32	9	3	10

[1]Refer to Figure 4 on page 22 for skid zone locations within each block.

Table 51. Block 2 treatments

Moisture Treatment	Tire Size	Passes	Operating Gear	Zone[1]
Moist (July)	28L-26	1	2	8
	28L-26	3	2	13
	28L-26	9	2	18
	28L-26	27	2	15
	67x34-25	1	2	17
	67x34-25	3	2	9
	67x34-25	9	2	14
	67x34-25	27	2	3
	73x44-32	1	2	11
	73x44-32	3	2	24
	73x44-32	9	2	20
	73x44-32	27	2	2
Wet (September)	67x34-25	1	2	23
	67x34-25	3	2	10
	67x34-25	4	2	19
	67x34-25	6	2	22
	73x44-32	1	2	1
	73x44-32	3	2	5
	73x44-32	6	2	6
	73x44-32	16	2	7
	73x44-32	1	3	16
	73x44-32	3	3	21
	73x44-32	9	3	4
	73x44-32	13	3	12

[1]Refer to Figure 4 on page 22 for skid zone locations within each block.

Table 52. Block 3 treatments

Moisture Treatment	Tire Size	Passes	Operating Gear	Zone[1]
Moist (July)	28L-26	1	2	15
	28L-26	3	2	17
	28L-26	9	2	16
	28L-26	27	2	1
	67x34-25	1	2	22
	67x34-25	3	2	20
	67x34-25	9	2	14
	67x34-25	27	2	2
	73x44-32	1	2	24
	73x44-32	3	2	6
	73x44-32	9	2	12
	73x44-32	27	2	11
Wet (September)	67x34-25	1	2	18
	67x34-25	3	2	4
	67x34-25	6	2	3
	67x34-25	6	2	10
	73x44-32	1	2	8
	73x44-32	3	2	21
	73x44-32	6	2	19
	73x44-32	9	2	9
	73x44-32	1	3	13
	73x44-32	3	3	25[2]
	73x44-32	8	3	7
	73x44-32	8	3	23

[1] Refer to Figure 4 on page 22 for skid zone locations within each block.
[2] This zone was located next to zone 24.

Appendix C. Litter Layer Amounts

Table 53. Litter layer amounts

Block	Location[1]	Oven-dried[2] pounds per acre	(kg/ha)
1	1	19053	(21355)
	2	27181	(30465)
	3	24500	(27460)
	4	18999	(21295)
	5	33827	(37915)
	6	23946	(26840)
	7	25329	(28390)
	8	16845	(18880)
	9	23121	(25915)
		mean = 23645	(26502)
2	10	9769	(10950)
	11	26333	(29515)
	12	12651	(14180)
	13	21783	(24415)
	14	16956	(19005)
	15	22068	(24735)
	16	18745	(21010)
	17	25936	(29100)
	18	12562	(14080)
		mean = 18537	(20777)
3	19	12901	(14460)
	20	15297	(17145)
	21	29509	(33075)
	22	23451	(26285)
	23	22572	(25300)
	24	28613	(32070)
	25	26021	(29165)
	26	16711	(18730)
	27	20337	(22795)
		mean = 21712	(24336)
mean, all blocks =		21298	(23871)

[1] See Figure 3 on page 21 for sample locations.
[2] Oven-dried at 65^{0}C to a constant weight.

Appendix D. Pre-treatment Descriptive Statistics for Soil Properties

Table 54. Pre-treatment descriptive statistics for soil bulk density

Block	Zones	Depth (cm)	n	Bulk Density (g/cc) mean	standard error	minimum	maximum
1	1-6	0-6	6	1.30	0.05	1.15	1.44
		35-41	6	1.62	0.01	1.58	1.67
		70-76	6	1.41	0.05	1.24	1.57
	7-12	0-6	6	1.22	0.05	1.09	1.39
		35-41	6	1.62	0.02	1.56	1.67
		70-76	6	1.50	0.04	1.36	1.62
	13-18	0-6	6	1.26	0.04	1.12	1.39
		35-41	6	1.57	0.02	1.49	1.66
		70-76	6	1.69	0.03	1.58	1.80
	19-24	0-6	6	1.33	0.04	1.21	1.44
		35-41	6	1.65	0.03	1.53	1.75
		70-76	6	1.40	0.07	1.07	1.55
2	1-6	0-6	6	1.26	0.03	1.13	1.35
		35-41	6	1.56	0.02	1.50	1.65
		70-76	6	1.72	0.02	1.65	1.77
	7-12	0-6	6	1.34	0.03	1.26	1.44
		35-41	6	1.59	0.02	1.54	1.68
		70-76	6	1.70	0.04	1.57	1.85
	13-18	0-6	6	1.29	0.02	1.22	1.32
		35-41	6	1.58	0.03	1.51	1.72
		70-76	6	1.41	0.05	1.27	1.56
	19-24	0-6	6	1.25	0.02	1.18	1.33
		35-41	6	1.62	0.02	1.53	1.70
		70-76	6	1.49	0.03	1.39	1.55
3	1-6	0-6	6	1.33	0.05	1.18	1.42
		35-41	6	1.55	0.03	1.44	1.64
		70-76	6	1.64	0.05	1.47	1.75
	7-12	0-6	5	1.26	0.03	1.14	1.31
		35-41	6	1.59	0.03	1.54	1.71
		70-76	6	1.63	0.04	1.52	1.75
	13-18	0-6	6	1.16	0.06	0.89	1.34
		35-41	6	1.56	0.03	1.45	1.65
		70-76	6	1.78	0.04	1.61	1.89
	19-24	0-6	6	1.29	0.02	1.19	1.36
		35-41	6	1.57	0.02	1.50	1.63
		70-76	6	1.71	0.06	1.57	1.91

Table 55. Pre-treatment descriptive statistics for soil total pore space

Block	Zones	Depth (cm)	n	Total Pore Space (%) mean	standard error	minimum	maximum
1	1-6	0-6	6	51.09	1.87	45.49	56.67
		35-41	6	38.90	0.56	36.93	40.44
		70-76	6	46.82	1.77	40.70	53.24
	7-12	0-6	6	54.00	1.98	47.47	58.83
		35-41	6	38.79	0.61	36.87	41.30
		70-76	6	43.49	1.52	38.90	48.62
	13-18	0-6	6	52.38	1.56	47.48	57.86
		35-41	6	40.72	0.86	37.54	43.76
		70-76	6	36.17	1.12	32.17	40.55
	19-24	0-6	6	49.90	1.51	45.56	54.26
		35-41	6	37.69	1.17	33.84	42.40
		70-76	6	47.13	2.75	41.54	59.47
2	1-6	0-6	6	52.59	1.26	48.89	57.20
		35-41	6	41.26	0.86	37.76	43.57
		70-76	6	35.20	0.65	33.37	37.84
	7-12	0-6	6	49.42	0.99	45.69	52.61
		35-41	6	40.05	0.84	36.45	41.95
		70-76	6	36.05	1.54	30.18	40.77
	13-18	0-6	6	51.45	0.63	50.10	53.84
		35-41	6	40.49	1.11	35.28	43.05
		70-76	6	46.59	1.88	41.02	51.97
	19-24	0-6	6	52.70	0.80	49.66	55.51
		35-41	6	38.91	0.96	35.85	42.31
		70-76	6	43.69	1.08	41.43	47.37
3	1-6	0-6	6	49.77	1.69	46.42	55.34
		35-41	6	41.50	1.15	38.27	45.61
		70-76	6	38.05	1.72	33.88	44.45
	7-12	0-6	5	52.46	1.19	50.47	57.08
		35-41	6	39.95	1.04	35.42	41.90
		70-76	6	38.64	1.30	34.10	42.47
	13-18	0-6	6	56.11	2.36	49.57	66.53
		35-41	6	41.21	1.20	37.66	45.17
		70-76	6	33.00	1.61	28.82	39.40
	19-24	0-6	6	51.23	0.90	48.61	55.11
		35-41	6	40.85	0.78	38.38	43.53
		70-76	6	35.31	2.11	27.86	40.81

Table 56. Pre-treatment descriptive statistics for soil capillary pore space

Block	Zones	Depth (cm)	n	Capillary Pore Space (%) mean	standard error	minimum	maximum
1	1-6	0-6	6	38.13	1.29	34.78	42.47
		35-41	6	34.39	0.35	33.62	35.66
		70-76	6	44.59	1.73	38.15	49.47
	7-12	0-6	6	38.59	0.79	36.69	42.13
		35-41	6	33.95	0.83	31.70	36.87
		70-76	6	41.52	1.71	35.87	46.79
	13-18	0-6	6	36.50	0.70	33.95	38.54
		35-41	6	32.15	0.34	30.90	33.16
		70-76	6	33.46	0.94	30.19	37.27
	19-24	0-6	6	34.47	1.30	29.93	38.93
		35-41	6	28.70	0.70	26.75	31.27
		70-76	6	42.18	2.58	30.59	48.54
2	1-6	0-6	6	39.75	1.40	35.66	45.21
		35-41	6	34.04	0.66	32.01	35.85
		70-76	6	32.83	0.85	30.69	36.77
	7-12	0-6	6	37.35	0.86	35.57	40.96
		35-41	6	33.95	0.76	31.37	36.93
		70-76	6	32.21	1.19	28.18	35.48
	13-18	0-6	6	38.92	1.39	35.90	45.21
		35-41	6	33.35	1.70	28.38	40.56
		70-76	6	44.53	1.71	39.21	49.10
	19-24	0-6	6	34.10	1.07	30.70	38.19
		35-41	6	29.31	0.48	28.19	31.43
		70-76	6	39.58	1.51	33.53	44.67
3	1-6	0-6	6	36.86	0.63	34.07	38.49
		35-41	6	33.95	0.88	30.99	37.67
		70-76	6	34.62	1.65	30.67	42.30
	7-12	0-6	5	37.61	2.23	30.73	43.67
		35-41	6	31.17	1.32	27.55	36.41
		70-76	6	34.47	0.77	32.57	37.31
	13-18	0-6	6	36.26	1.21	32.21	39.51
		35-41	6	31.87	0.44	30.66	33.65
		70-76	6	30.60	1.22	27.38	34.07
	19-24	0-6	6	35.53	0.85	33.56	39.54
		35-41	6	31.19	0.31	30.24	32.27
		70-76	6	30.00	1.88	26.05	38.00

Table 57. Pre-treatment descriptive statistics for soil non-capillary pore space

Block	Zones	Depth (cm)	n	Non-capillary Pore Space (%) mean	standard error	minimum	maximum
1	1-6	0-6	6	12.96	1.75	7.65	20.04
		35-41	6	4.52	0.45	3.09	5.92
		70-76	6	2.23	0.38	0.93	3.77
	7-12	0-6	6	15.40	2.26	7.02	21.30
		35-41	6	4.85	0.55	2.43	6.41
		70-76	6	1.96	0.37	0.87	3.03
	13-18	0-6	6	15.88	1.36	12.46	20.57
		35-41	6	8.57	0.66	6.64	10.60
		70-76	6	2.71	0.46	1.75	4.70
	19-24	0-6	6	15.42	0.97	11.22	18.53
		35-41	6	8.99	1.41	5.23	14.82
		70-76	6	4.95	2.46	0.17	14.18
2	1-6	0-6	6	12.84	1.96	6.98	19.43
		35-41	6	7.21	1.16	3.54	10.99
		70-76	6	2.37	0.34	1.07	3.37
	7-12	0-6	6	12.08	1.43	6.91	16.00
		35-41	6	6.10	0.80	3.38	8.57
		70-76	6	3.85	1.10	2.01	9.21
	13-18	0-6	6	12.54	1.19	8.63	17.01
		35-41	6	7.14	1.10	2.49	10.38
		70-76	6	2.07	0.22	1.53	2.87
	19-24	0-6	6	18.60	1.52	11.48	22.66
		35-41	6	9.60	1.32	5.38	14.12
		70-76	6	4.10	2.01	0.07	13.83
3	1-6	0-6	6	12.91	2.10	7.93	21.27
		35-41	6	7.55	1.46	5.14	14.62
		70-76	6	3.43	1.05	1.26	8.06
	7-12	0-6	5	14.85	2.62	8.15	20.56
		35-41	6	8.78	1.65	4.16	12.88
		70-76	6	4.17	1.24	0.11	7.41
	13-18	0-6	6	19.85	2.72	15.91	33.38
		35-41	6	9.34	1.38	5.91	12.97
		70-76	6	2.39	0.76	0.74	6.00
	19-24	0-6	6	15.70	1.18	12.08	20.86
		35-41	6	9.67	0.89	6.90	13.20
		70-76	6	5.31	1.24	1.62	9.25

Table 58. Pre-treatment descriptive statistics for soil saturated hydraulic conductivity

Block	Zones	Depth (cm)	n	Saturated Hydraulic Conductivity (cm/hr.) mean	standard error	minimum	maximum
1	1-6	0-6	6	126.08	73.48	2.25	453.10
		35-41	5	0.20	0.07	0.06	0.44
		70-76	6	0.01	0.00	0.00	0.03
	7-12	0-6	6	56.99	22.73	8.43	153.11
		35-41	6	0.25	0.05	0.10	0.41
		70-76	6	0.01	0.01	0.00	0.04
	13-18	0-6	5	42.47	17.12	11.20	107.78
		35-41	6	0.74	0.17	0.16	1.25
		70-76	6	0.03	0.02	0.00	0.12
	19-24	0-6	6	55.99	19.95	3.07	140.61
		35-41	6	0.54	0.16	0.16	1.11
		70-76	5	0.02	0.02	0.00	0.09
2	1-6	0-6	6	118.41	51.60	11.30	337.12
		35-41	6	0.51	0.10	0.11	0.83
		70-76	6	0.01	0.01	0.00	0.03
	7-12	0-6	5	9.06	1.39	6.18	13.62
		35-41	6	0.97	0.24	0.08	1.75
		70-76	6	0.02	0.01	0.00	0.08
	13-18	0-6	5	27.80	6.46	16.80	51.54
		35-41	6	0.53	0.17	0.03	1.11
		70-76	6	0.01	0.00	0.00	0.03
	19-24	0-6	6	11.24	2.46	1.75	19.06
		35-41	5	0.27	0.11	0.11	0.68
		70-76	6	0.07	0.05	0.00	0.33
3	1-6	0-6	5	25.18	9.21	10.72	61.34
		35-41	6	1.12	0.28	0.26	2.05
		70-76	6	0.03	0.01	0.00	0.07
	7-12	0-6	6	70.37	31.16	15.06	199.21
		35-41	5	0.71	0.19	0.04	1.13
		70-76	6	0.10	0.06	0.00	0.35
	13-18	0-6	5	32.55	5.96	19.06	54.46
		35-41	6	2.91	0.64	1.72	5.74
		70-76	6	0.16	0.10	0.00	0.61
	19-24	0-6	6	57.80	18.80	15.86	126.20
		35-41	6	1.59	0.21	0.62	2.15
		70-76	5	0.16	0.09	0.02	0.51

Appendix E. Water Table Depths

Table 59. Water table depth during moist (July) trial

Well No.[1]	Depth to water from soil surface, in. (cm)	
1	> 60.0	(> 152)
2	> 60.0	(> 152)
3	47.2	(120)
4	> 60.0	(> 152)
5	> 60.0	(> 152)
6	15.7	(41)
7	> 60.0	(> 152)
8	> 60.0	(> 152)
9	> 60.0	(> 152)
10	52.6	(134)
11	57.0	(145)
12	45.2	(115)
13	45.2	(115)
14	48.3	(123)
15	40.6	(103)
16	42.9	(109)
17	39.8	(101)
18	> 60.0	(> 152)
19	> 60.0	(> 152)
20	43.4	(110)
21	26.5	(67)
22	57.2	(145)
23	52.8	(134)
24	19.9	(51)
25	16.5	(42)
26	20.9	(53)
27	38.0	(97)

[1] Refer to Figure 3 on page 21.

Table 60. Water table depth during wet (September) trial

Well Number[1]	Depth to water from soil surface, in. (cm)			
	September 8, 1986		September 25, 1986	
1	2.4	(6)	12.6	(32)
2	1.6	(4)	5.1	(13)
3	4.3	(11)	9.4	(24)
4	1.2	(3)	12.2	(31)
5	4.3	(11)	15.0	(38)
6	0	(0)	3.1	(8)
7	1.2	(3)	7.9	(20)
8	4.7	(12)	15.4	(39)
9	6.7	(17)	18.5	(47)
10	7.1	(18)	18.5	(47)
11	5.5	(14)	13.4	(34)
12	6.3	(16)	20.9	(53)
13	6.3	(16)	15.0	(38)
14	3.9	(10)	11.4	(29)
15	2.4	(6)	10.6	(27)
16	2.8	(7)	7.5	(19)
17	2.4	(6)	5.1	(13)
18	0.8	(2)	5.5	(14)
19	2.8	(7)	7.1	(18)
20	+0.8	(+2)	5.9	(15)
21	1.6	(4)	5.9	(15)
22	0.4	(1)	4.7	(12)
23	0.8	(2)	4.7	(12)
24	1.6	(4)	5.5	(14)
25	1.2	(3)	6.7	(17)
26	1.2	(3)	6.7	(17)
27	3.9	(10)	11.4	(29)

[1] Refer to Figure 3 on page 21.

Appendix F. Skidder and Tire Specifications

Table 61. Skidder specifications

Field Trial	Item	Skidder 1	Skidder 2
Moist (July)	Skidder	1981 Franklin 170 (ser. no. 11365)	1985 Franklin 170 (ser. no. 12764)
	Engine	Detroit 4-53 turbo	Cummins 6BT5.9
	Governed RPM	2650	2500
	Axle model	230	230
	Differential ratio	7.6:1	8.55:1
	Grapple	M-33	M-33
	Tires used	67x34-25	28L-26, 73x44-32
Wet (September)	Skidder		1985 Franklin 170 (ser. no. 12764)
	Engine		Cummins 6BT5.9
	Governed RPM		2500
	Axle model		230
	Differential ratio		8.55:1
	Grapple		M-33
	Tires used		67x34-25 73x44-32

Table 62. Tire specifications

Field Trial	Item	Tire Size 28L-26	67x34-25	73x44-32
Moist (July)	Manufacturer	Firestone	Goodyear	Firestone
	Plies	10	10	12
	PSI: front(rear)	22(22)	18(21)	20(20)
	Mean lug depth (in.)	1.92	2.22	2.6
	Single tire and rim weight (lbs.)	970	-	1525
	cleats/tire	15	14	20
	condition	100%	75%	100%
Wet (September)	Manufacturer		Firestone	Firestone
	Plies		10	12
	PSI: front(rear)		20(20)	20(20)
	Mean lug depth (in.)		3.0	2.6
	Single tire and rim weight (lbs.)		-	1525
	cleats/tire		14	20
	condition		100%	100%

Appendix G. Load Weights

Table 63. Load weights

Field Trial	Tire Treatment	Start Weight Pounds (kg)	End Weight Pounds (kg)
Moist (July)	28L-26 67x34-25 73x44-32	6440 (2921) 6815 (3091) 7010 (3180)	6545 (2969)[1] 5840 (2649) 6750 (3062)
Wet (September)	67x34-25 73x44-32	7100 (3221) 7210 (3270)	6580 (2985) 6355 (2883)

[1] This was an error in weighing.

The vita has been removed from the scanned document