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IMPACTS OF GROUND-BASED LOG SKIDDING ON FOREST SOILS IN WESTERN MENDOCINO COUNTY

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Yarding with a crawler tractor in Hare Creek, Mendocino County, California

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ABSTRACT

Soil compaction and displacement resulting from log skidding with ground-based vehicles was studied on two areas of Jackson Demonstration State Forest, located in western Mendocino County. Soils are clayey at depth and support stands of second-growth coast redwood and Douglas- fir. Bulk density was found to be increased about 20 % in the surface six-inch zone on primary skid trails, but excavation had removed the surface horizon in many of the sample locations. Compacted densities of approximately 1.40 g/cm^3 were found. Primary and secondary skid trails generally occupied about 12 % of the land base. Final densities on heavily used skid trails created during dry summer and moist fall months on the Hare Creek site were nearly identical, and the soils were considered moisture insensitive. Tillage experiments showed that rock rippers were ineffective on steep, rocky primary trails at the James Creek sites. Winged subsoilers were able to effectively till dense soils at the flatter, less rocky Hare Creek site. Measurements of planted seedling heights show that statistical differences do not exist in tilled and untilled soils at both sites. Several factors besides soil compaction complicated the height growth analyses.

Keywords: soil compaction, tillage, site productivity, tractor yarding

INTRODUCTION

Over the past 35 years, researchers have documented the impacts that ground-based skidding machines can have on the forest soil resource. The range of the effects reported has varied greatly, depending in part on the type of soil studied, types of machines operated, the degree of excavation that occurred, and the sampling methods used. Confusion among resource professionals still exists today as to when one should be concerned about soil compaction, and what the best management strategies are to protect the soil resource for future generations of forest crops. Sufficient research on forest soils has now been done to replace many of the misconceptions with factual information.

Results of studies documenting tractor logging impacts done on Jackson Demonstration State Forest (JDSF) in the redwood region of western Mendocino County over the past six years are presented in this paper. Curiously, while large crawler tractors have been used on steep, clayey soils in the redwood region for over sixty years, little research has been done here on the impacts of these machines in terms of on-site modification. Harvesting very large old-growth redwood with tractors in the past affected large percentages of the land base, since skid roads and soil beds to reduce breakage were needed. Most of the research on soil compaction and displacement has been done in the Douglas-fir region of the Pacific Northwest and in the southern pine region of the United States.

While a complete review of the literature on this subject is beyond the scope of this paper, a synopsis of past work will familiarize the reader with the subject area. Soil compaction can be defined as an increase in bulk density, or dry soil weight per unit volume. When a soil is compacted, pore size distribution undergoes the most alteration. Soils are made up of solids, voids between the particles, water, and air. If a load is applied over the soil, and the soil does not have sufficient strength to bear the load, it will consolidate. A proportion of the largest voids, or "macro-pores," are converted to smaller voids, or "micropores." For example, on the Tahoe National Forest in California, various types of skidding equipment reduced macropore space 43% on primary skid trails (Cafferata 1983).

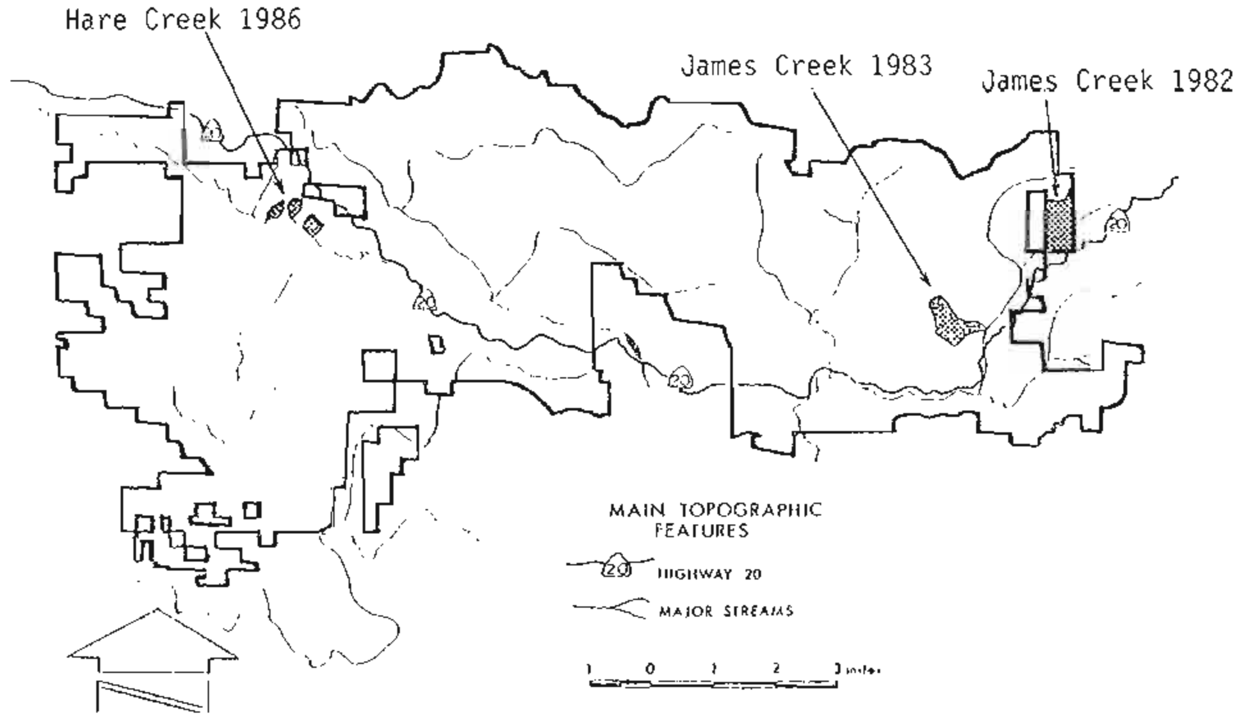
Compacting a forest soil does several things. Of fundamental importance is the fact that this process can reduce forest growth. Many researchers have documented reductions in growth and survival of young trees growing in compacted skid trails (Steinbrenner and Gessel 1955, Froehlich 1979-a). This can occur because of the altered pore size distribution, which radically decreases the rates that air and water can move downward through the compacted zone and reach tree roots. Of even greater significance is the increased resistance fine roots encounter when soil strength is increased through compaction. Greacen and Sands (1980) state that root elongation rates decrease exponentially with increases in soil strength. Root penetration through pores in the soil that are smaller in diameter than the roots themselves can occur only by overcoming the strength of the soil. In addition, increases in physical resistance of soil to root penetration may cause nutrient deficiencies to occur in seedlings, since the volume of soil available for extraction becomes limited (Whitaker 1983).

Due to these changes, the removal of the litter layer, and often the nutrient-rich A horizon of the soil, most studies show a nearly linear relationship between increases in soil density and decreases in seedling height growth (Froehlich and McNabb 1983). The range in the reduction of height growth is generally 5 to 50 percent (Froehlich 1979- a). Most of the literature states that soil compaction and associated soil disturbance is likely to cause some reduction in growth of individual trees at older ages as well (Helms 1983). For example, Froehlich (1979-a) noted reduced height growth of ponderosa pine on compacted areas in southwest Oregon after 17 years. Exceptions have been found, however. On ash soils in coastal Washington near Cosmopolis, where an 80 percent increase in bulk density occurred, no statistical difference in height existed for Douglas-fir after 8 years (Scott, per. comm.) No heavy clay B horizon exists on these soils. Scott states that this is not a rare phenomenon on these types of soils.

Apparently, long term growth reductions for the entire life of a tree from compaction are most likely to happen where there are heavy clay B horizons and/or the removal of the A horizon occurs. Therefore, simply recording increases in bulk density in the surface zone may not accurately predict long term growth losses for some soils. Implications of soil compaction on stand growth were studied by Helms (1983) on the Tahoe National Forest. For a 15-year-old ponderosa pine plantation, the long term projection of growth differences between heavily compacted zones and undisturbed areas were between one-half and one site index class. Soils here are volcanic in origin and have heavy clay B horizons; no excavation occurred on very gentle slopes. Similar results could not be produced for a 7-year-old pine plantation growing on a sandy loam soil derived from granitic till.

In addition to biological implications, compaction can significantly alter the hydrologic regime of forest soils. Undisturbed forest soils al-

Figure 1. The three timber sales studied on Jackson Demonstration State Forest.



most always have infiltration capacities (i.e., the rate precipitation can enter the soil profile) greater than precipitation intensities for that area (Satterlund 1972). Numerous studies have documented how compaction from logging vehicles has resulted in greatly reduced infiltration and increased surface erosion (Dyrness 1965, Johnson and Beschta 1980). Before 1973, when legislation was enacted that required drainage of skid trails in California, large quantities of soil sometimes eroded from skid trail networks.

Predicting how much compaction will occur from ground skidding on forest soils is exceedingly complicated. Many factors are interrelated and are of great importance. The type of soil being impacted is critical. The percentages of sand, silt, and clay dictate how much soil strength exists and how the soil will be altered. Volcanic and sedimentary derived soils with high percentages of clay are much more compactible than granitic soils made up of sandy loams. Soil structure plays a large role in how much compaction will result. Also of concern are low organic matter content and high moisture content. The latter factor may result in high compaction levels if certain conditions exist (e.g., fine textured soils with expandable clay minerals).

Different types of logging vehicles vary in their potential for creating compaction problems. Light machines that exert low ground pressure over a wide, flexible track reduce surface disturbance and minimize compaction (Froehlich 1978). The amount of compaction that occurs increases as the protective slash and litter over the mineral soil is lost. The number of trips a given vehicle makes, however, is the most important factor of all. Soil densities increase rapidly during the first few trips, but the rate of change progressively decreases with successive trips (Froehlich et al. 1980). After many trips, the difference in machine types is minimal. Due to all these variables, increases in soil density on skid trails can range anywhere from 10 to 80 percent (Froehlich 1979-a).

Unfortunately, natural recovery from soil compaction is extremely slow under climatic conditions found in temperate regions of the western United States (Vanderheyden 1980). Strategies to reduce this problem currently include: 1) cable yarding where feasible to avoid the use of ground skidding, 2) pre-flagging skid trail locations to insure that spacing is far enough apart to minimize the percentage of the land base being compacted, 3) operating equipment when soil strength is high (i.e., soils are dry or frozen), and 4) using tillage equipment, such as the "winged subsoiler," to ameliorate heavily compacted areas (Froehlich and Miles 1984; Froehlich et al 1981; Alexander and Poff 1985).

STUDY AREAS

The results presented in this Note are from studies completed on two areas in Jackson Demonstration State Forest. The first sites where we sampled soil compaction are located in the James Creek drainage, while the second area is found in the Hare Creek watershed. Brief summaries follow of the physiographic and vegetative types of these areas, and the treatments that were implemented on them (see Figure 1).

James Creek

The James Creek watershed is located about 20 miles east of the town of Fort Bragg, California, and the Pacific Ocean. It is a 5000- acre tributary of Big River, which enters the sea at Mendocino. James Creek is near the eastern boundary for coast redwood (Sequoia sempervirens), which requires an abundance of cool, foggy summer days. In addition to redwood, Douglas-fir (Pseudotsuga menziesii), tanoak (Lithocarpus densiflorus), Pacific madrone (Arbutus menziesii), and chinquapin (Castanopsis chrysophylla) exist in the overstory. Understory vegetation consists of rhododendron (Rhododendron macrophyllum), huckleberry (Vaccinium ovatum), salal (Gaultheria shallon), blueblossom (Ceanothus thyrsiflorus), wax myrtle (Myrica californica), canyon live oak (Quercus chrysolepis), bigleaf maple (Acer macrophyllum), and hairy manzanita (Arctostaphylos columbiana). Elevations at the study sites range from 1200 to 1600 feet. Precipitation occurs primarily as rainfall, and averages over 60 inches annually. Summer maximum temperatures are near 100° F, and winter minimums are slightly below freezing.

The soil types found here are included in the Yellowhound-Kibesillah complex (loamy-skeletal, mixed, isomesic Ultic Haplustalfs). They have surface horizon textures classified as very gravelly loams, and very gravelly clay loam B horizons. Soil depth is generally 40 inches or less. The soils are derived from the Franciscan formation, which is made up of highly fractured sandstone and shale. The potential for mass failure events with these soil types is high. The droughty surface layer greatly reduces seedling survival on south/southwest facing slopes. The terrain is youthful, and continues to be actively uplifted by tectonic forces. Slopes range from 15 to 70 percent, with an average of 50 percent.

Our study utilized 30 acres of the 280-acre James Creek 1982 Timber Sale (JC 82) and 87 acres of the 215-acre James Creek 1983 Timber Sale (JC 83). These areas were logged for the first time in the late 1950's using large crawler tractors with chokers. Old-growth redwood and Douglas-fir were selectively logged at that time, so that between 25 and 30 percent of the existing stand was retained. The remaining old-growth was cut in the second entry. The harvesting prescription was to remove all conifers larger than 22 inches in diameter at breast height (dbh). Approximately 135 square feet of basal area per acre, or 20,000 board feet, was removed. Site class ranges from II to IV here (McArdle 1949), largely dependent on aspect and topographic position.

Timber harvesting for the 1982 and 1983 sales consisted of crawler tractor yarding the upper slopes, and cable yarding below a midslope road. Crawler tractors of Caterpillar D-7 size were used. In JC 82, about 30 acres of Unit B were studied as a prototype for a larger study in JC 83. Tractor-logged compartments A and C were utilized for the compaction study in the 1983 sale; unit A was 30 acres, while unit C was 57 acres. Some of the skid trails constructed for the 1958 logging were reused for the more recent harvesting, but many had to be abandoned since they went down small drainages. Trails on the steeper slopes were deeply excavated down to subsoil or bedrock.

Hare Creek

The Hare Creek drainage is found on the west end of JDSF. It is a relatively small 5000-acre watershed that enters directly into the Pacific Ocean just south of Fort Bragg and extends inland six miles. The climate here is considerably moister than that found in James Creek, since summer fog is much more prevalent. Summer maximum temperatures are in the low 80°'s, and winter minimums are near freezing. Precipitation, in the form of rain, falls at a rate of 45 inches per year, with 90 percent coming between October and April. Overstory tree species found here include redwood, Douglas-fir, grand fir (Abies grandis), western hemlock (Tsuga heterophylla), and bishop pine (Pinus muricata). The hardwood component of the stand is much less significant than that found in James Creek, and primarily consists of tanoak. Understory vegetation is similar to that found farther east, with the addition of swordfern (Polystichum munitum). Elevations range from 400 to 1000 feet.

The soils in Hare Creek are classified as Irmulco, Tramway (fine-loamy, mixed, isomesic Ultic Tropudalfs) and Van Damme (clayey, mixed, isomesic Typic Tropudults). They are deeper than the more skeletal soils found in James Creek, with soil depth commonly reaching 60 inches or more. The surface textures are generally loams and the B horizons are clay loams. Subsoils have between 35 and 45 percent clay. These soils have a lower gravel component (0-10%) than the soils in James Creek. Slopes range from 10 to 60 percent, and average 40 percent.

Old-growth harvesting took place in Hare Creek from 1880 to 1900 and was accomplished mainly with steam donkeys and railroads built along the creek. Second-growth harvesting began in the late 1960's and continues today. Our soil compaction study sites here sampled 70 acres of the 130-acre Hare Creek 1986 Timber Sale (HC 86). This area of the sale was entirely clearcut, with approximately 350 square feet of basal area per acre (60,000 board feet per acre) removed with ground skidding machines. Caterpillar D-7 sized machines were used primarily, with a small percentage of the volume removed by Caterpillar 518 sized rubber- tired skidders. Site class here is site II (McArdle 1949). Units A and C of HC 86 were studied; "A" was 30 acres, while "C" occupied 40 acres. New skid trails were constructed for both units. No excavation was required for many of the trails, but on the steeper ground, excavation of 40 inches or more occurred. As was the case in the JC 82 and JC 83 sales, the timber sale contract specified there were to be 100 feet between skid trails. Only equipment with winch line and chokers was used on all the sites.

METHODS

In both the James Creek and Hare Creek sale areas, similar study designs were utilized. The primary components of the sampling consisted of: 1) mapping all skid trails in a given unit, 2) making soil density measurements both on and off skid roads, 3) tilling selected areas and remeasuring densities, 4) excavating cross sections of skid trails after tilling, and 5) making measurements of planted seedlings in skid trails. Brief descriptions of how these items were accomplished in each area follows.

Mapping Skid Trails

For JC 83, the sale administrator sketched on a large scale map all the skid trails utilized by the current logging and recorded estimates of the number of trips by the crawler tractors. It was noted which were preexisting and which were newly constructed, since many of the skid trails used in 1958 could not be reused because of improved Forest Practice standards. In the Hare Creek sale, large scale (1:6000) aerial photographs were used to map the skid trails constructed.

To determine the area of a unit disturbed by skid trails, the total length of the combined skid trails was obtained by using a planimeter. A trail width of 13 feet was assumed, based on previous measurements made by Cole (1983) on tractor trails studied in Hare Creek. Multiplying the length by the average width and dividing by the total acreage in the unit yielded percent of the landbase disturbed.

Soil Density Measurements

Density measurements were obtained the same way for both the JC 83 and HC 86 sale areas. Major landings were first identified on the ground. Sample plot locations were located at 300-foot (slope distance) intervals up from the landings on primary skid trails (see Figure 2). Ten plots were established in each sale unit. At each plot location, ten-foot wide transects were laid out across the most heavily impacted portion of the skid trails. Nuclear density gauges were used to record soil bulk density. Measurements were made at three equally spaced positions along the transects (i.e., 2.5, 5.0, and 7.5 feet). Density readings were made at a depth of six inches. Additionally, two sites were chosen on uncompacted soils off skid trails as near as possible to each plot for control measurements. For these locations, the surface litter was removed, and density measurements were again made at the six-inch depth. None of the bulk densities reported here are corrected for stone content.

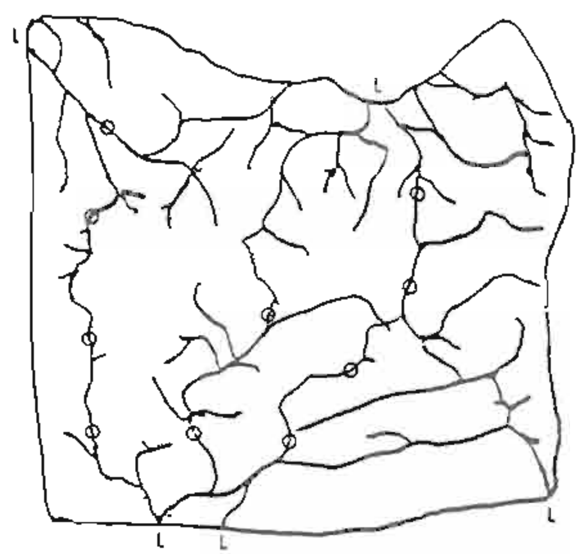


Figure 2. Skid trail layout for the 40-acre Hare Creek 1986 Unit C. Plot locations (o) for bulk density measurements and landings (L) are indicated.

Skid Trail Tillage

Two types of tilling devices were studied. In the James Creek sales, standard rock rippers were utilized to loosen the compacted soil. Specifically, a Caterpillar D-6D crawler tractor was equipped with a five-tine, 24-inch rock ripper for both the JC 82 and JC 83 sites (see Figure 3). Only the JC 83 area was monitored for soil density changes. Unit A in that sale was tilled with the rock ripper in October 1983, and the ten plots previously established were remeasured in 1984, after one over-wintering period. Unit C was the untilled control, and its plots were measured for density at the same time.

A device specifically designed for skid trail tillage called a "winged subsoiler" was tested in the Hare Creek sale. First developed at Oregon State University, it consists of three 48-inch shanks fitted with winged shoes that lift and fracture compacted soil. Mr. Ed Fields of Monroe, Oregon modified and patented the device with individual shank-tripping mechanisms that automatically reset after encountering roots or large rocks (see Figure 4). In addition, it is self-drafting; this means that it is able to pull itself into the ground and remain at a certain depth. To attach the winged subsoiler to the JDSF Caterpillar D-7E crawler tractor, a wheeled "dolly" was required. The preferred arrangement would have been to directly attach the device to the tractor with a stump-splitting bracket. All the skid trails in units A and C which could be reached with the winged subsoiler and dolly apparatus were tilled in September 1987. Half of the soil density plots in each unit were randomly selected to be tilled, and the remaining half served as controls. When the tractor and subsoiler came to control plots, the shanks were lifted out of the ground. All the plots were remeasured for soil density after one over-wintering period in the summer of 1988.

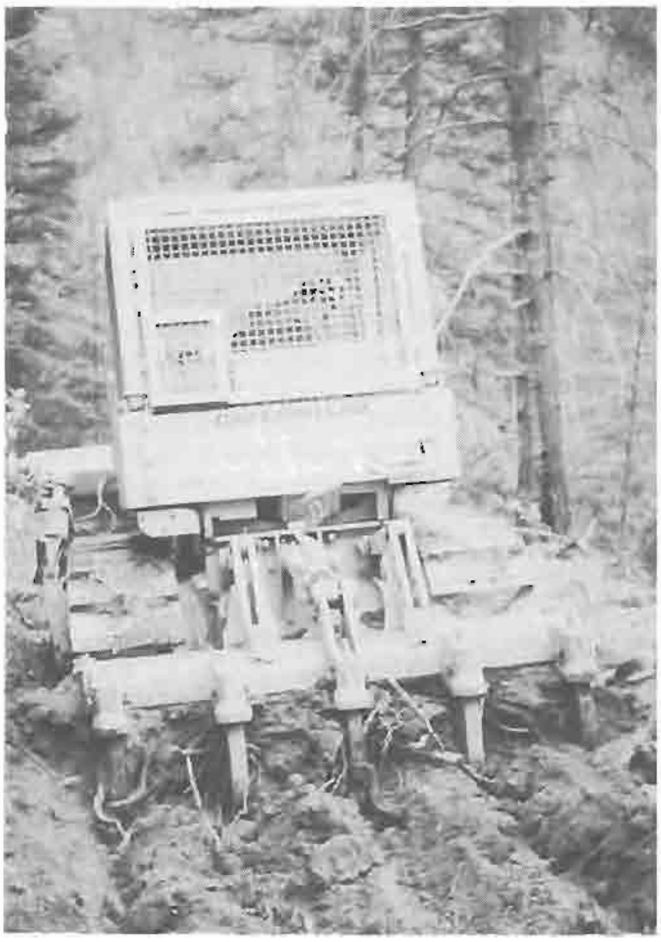


Figure 3. Caterpillar D-6C crawler tractor with a five-tined rock ripper in James Creek 1982 sale.

Excavated Cross Sections

In order to evaluate the percentage of the compacted skid trail soil actually being loosened and fractured through tillage, a limited number of cross sections was excavated. In the JC 82 sale, this was the only mechanism we had to monitor the effectiveness of the rock ripper. Three randomly located transects were established here, and measurements were made at six-inch intervals. A tape was stretched between two stakes, and the distances down to the hard, compacted soil surface were recorded. After tillage, the same transects were excavated down to hard, unfractured soil, and similar measurements were made. No cross section measurements were taken in the JC 83 sale. For each of the two Hare Creek units, three of the five plots that underwent tillage were randomly chosen for excavation. A similar procedure as that used in James Creek was followed.

Seedling Measurements in the Skid Trails

During the winter of 1984-85, the JC 83 sale was planted with 2-0 Douglas-fir and 1-0 redwood bare root stock at a rate of 300 trees per acre. Plots 25 feet in length and the width of the trail were established at 175-foot intervals along skid trails in

Figure 4. Winged-subsoiler tilling device on dolly pulled by a Caterpillar D-7E crawler tractor.

both units. During November 1985, the heights of all the planted seedlings in these plots were measured. In May 1989, planted seedling heights were remeasured and natural seedlings were also measured.

To evaluate seedling growth in HC 86, short transects of plug #5 redwood were established during February 1988 in Unit C. In a representative tilled and untilled skid trail with similar slopes and aspects, 25 trees were planted and marked with flag pins. For the undisturbed areas off skid trails, three transects of ten trees were planted with matching slopes and aspects. The heights of all the trees were measured in November 1989.

RESULTS AND DISCUSSION

Area Disturbed by Skid Trails

In the JC 83 sale, Unit A had 10 percent of its area in primary and secondary trails, while Unit C had 13 percent. Very similar percentages were recorded for the two Hare Creek 1986 units. Unit A had 14 percent of its area in primary and secondary trails, while Unit C had 10 percent. The combined average for all four of the units studied was 12 percent.

Most of the studies done in the past have reported considerably higher percentages than these on JDSF. For example, Froehlich (1979-a) states that skid trails commonly account for 25 to 35% of a tractor logged site when restrictions are not placed on operators. Steinbrenner and Gessel (1955) reported 26% in Washington, Dyrness (1965) also found 26% in Oregon, and Hatchell, et al. (1970) noted 32% in South Carolina and Virginia. Subsequent entries into a unit can increase the area in trails to as much as 80% of the soil surface (Froehlich et al. 1981).

More recently, mechanized harvesting without restrictions on machine movement has been shown to cause large percentages of the land base to be compacted. Laing and Dashiell (1983) reported 42% of a unit in Western Oregon was heavily compacted when a feller-buncher and rubber-tired skidders operated on flat ground. Murdough and Jones (1984) found 38% of a sale area in the Oregon Cascades with significant compaction from feller-buncher and skidder logging. Zaborski (1989) noted that 54% of a unit with more systematic logging was impacted from mechanized harvesting in Eastern Oregon, with about 25% of the area altered beyond the USFS's definition of detrimental compaction.

In order to reduce the amount of soil compacted during ground skidding, the approach of flagging skid trails in advance of logging has been tried. The operators are then required to stay on these designated areas. When skid trails were kept 100 feet apart in Western Oregon, Froehlich et al. (1981) reported only 11 percent of the area covered with trails. If fallers can fell trees towards the trails, the line pulling distance is about the same as with conventional logging. Sidle and Drlica (1981) found that 13.6% of a unit was compacted in Western Oregon where main skid trails were flagged, but the operator moved off them in several locations to facilitate timber removal. In an earlier study done in Hare Creek on JDSF, Cole (1983) reported 12.4% of a unit in skid trails on an area with pre-constructed trails, and 12.6% in an area with conventional logging. These percentages were nearly identical because the operator was required to keep spacing of skid trails 100 feet apart by the contract.

Observations made during logging on our study sites indicate that the percentages we recorded are low due to the general adherence of the operator to the contractual agreement of 100-foot spacing and the typically steep ground on which they were working. Pre-flagging was usually not done, but Sale Officers were often on the sites to enforce the contract language. Slopes from 30 to 50+ percent require excavation for skid trails and this is expensive to operators. Therefore, it is to their advantage to keep spacing reasonably wide. The unit with the highest percentage in skid trails, HC 86 A, was the flattest, with slopes from 10 to 40 percent. No flagging of trails was done, and the operator was not required to keep adequate trail spacing. Single passes with the tractors occurred off constructed skid roads on this unit, but did not show on the aerial photos as skid trails. Therefore, it is likely that at least 20 percent of the unit was compacted to some degree.

Table 1. Soil densities at both sales on and off major skid trails.

	JC 83	HC 86
	(g/cm^3)	
Undisturbed Area	1.24	1.15
Major Skid Trail	1.49	1.36
change in bulk density	0.25	0.21
percent change	20	18

Soil Density Measurements

A summary of the nuclear probe bulk density data collected prior to tillage is presented in Table 1. Density measurements were approximately 20 percent higher on compacted skid trails in JC 83 when compared to the undisturbed plots. The undisturbed and compacted averages were found to be significantly different for both units at the 0.05 level. In HC 86, we found density on the compacted trails averaged 18 percent higher than that measured off the trails. Again, the means for the undisturbed and compacted areas were significantly different at the 0.05 level in both units. The majority of the plots in James Creek were deeply excavated, with average cut banks of four feet. In Hare Creek, much less excavation occurred. The average cut bank was only one foot. Therefore, the percent increase in density in James Creek is partly due to exposure of more dense subsoil and rock.

The range of reported increases in bulk density resulting from ground skidding varies greatly. Where similar sampling techniques have been used and soils have had a significant clay content, however, comparable results have been reported. For example, Aulerich et al. (1974), measured a 21 percent increase in density in the surface 6-inch zone of major trails with a clay loam texture. In that study, small crawler tractors were used to thin second-growth Douglas-fir in Western Oregon. In a stand of ponderosa pine in Central Oregon where essentially no recovery had taken place in 16 years since tractor logging, Froehlich (1979-b) reported an increase in density of 18 percent in the surface 6-inch zone of a sandy clay loam soil. Finally, Froehlich et al. (1980) noted a 20 percent increase in density in the surface eight inches of a loam soil with 25 percent clay in the Sierra Nevada Mountains of California. Crawler tractors (D-6 size) had made 20 trips on soils with moisture contents varying from 20 to 25 percent.

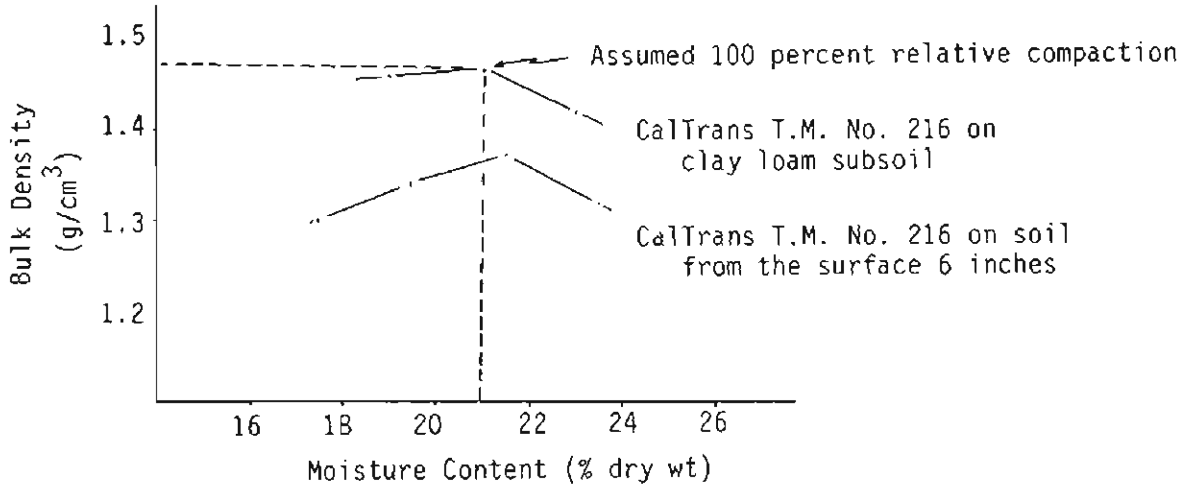
Moisture-Density Relationships

Most of the factors that can influence the extent of soil compaction on a given skid trail cannot be altered, except for the machine type and the moisture content. The initial soil density, organic matter content, soil strength, soil structure, and soil texture are given. On primary trails where more than 20 turns will be skidded, even machine type is often not important. Therefore, moisture content is the only variable controlling compaction. How important is the moisture content?

Froehlich and McNabb (1983) report that while limiting machine operations to times when soil moisture is below a specified level may reduce compaction on some soils, many others have nearly flat moisture-density curves and compact to similar densities over a wide range of soil moistures. The amount of compaction that occurs at different moisture contents appears to be related to particle size distribution and clay mineralogy of the soil (McNabb, unpubl. data). Compaction of both well-graded coarse-textured soils (i.e., those with an even distribution of size classes) and fine-textured soils with expandable clay minerals are affected by moisture content. Poorly graded coarse-textured soils and fine-textured soils with non-expanding clay minerals compact to similar bulk densities over a range of moisture contents.

Moisture-density curves for soil from HC 86 Unit C are presented in Figure 5. The soil in the Hare Creek sale can be categorized as fine-textured with mostly non-expanding clay minerals (both the non-expanding clay mineral kaolinite, and vermiculite, a limited expansion clay mineral, are present). CalTrans Test No. 216, which is used to evaluate the relative compaction of a soil compared to optimal compac-

Figure 5. Moisture-density relationships from a laboratory test on soil taken from the surface 6 -inch zone and subsoil taken from a skid trail in Hare Creek Unit C.



tion desired for roadbed sites, produced the two curves. In the laboratory, a 10- pound hammer was dropped 25 times on soil (sieved to remove stones 3/4 inch and larger) in a mold at a given moisture content; several runs at different moistures produced the curves displayed. The most dense soil was produced at a moisture content of slightly more than 21 percent for both soil taken from an undisturbed 0-6-inch zone, and clay loam subsoil taken from a skid trail. Maximum density at this moisture level was 1.37 g/cm^3 for the soil taken from the surface six-inch zone, and this correlates well with the average densities measured on the trails.

Soil moisture was not measured when the logging took place, but in the HC 86 sale, Unit C was logged during July and August, when moisture levels are below 20 percent on these types of soils. Unit A was logged in November and December, between rainy periods. Six inches of rain had fallen before skidding; 9.5 inches by the time skidding was finished. The moisture content was likely to have been approximately 27 percent, based on sampling in an adjacent watershed during the various months of the year (see Figure 6). While off-trail densities were slightly different for units A and C (1.12 vs. 1.19 g/cm^3, respectively), the final densities on primary skid trails in both units were nearly identical (1.37 and 1.35 g/cm^3 for Units A and C, respectively). Therefore, this soil type is fairly moisture insensitive, and there is little or no value in using moisture-density curves produced in a laboratory test to pinpoint a target moisture content to avoid compaction problems.

Recording tensiometers in a watershed adjacent to Hare Creek show that for the majority of the months when ground skidding is practiced in Mendocino County (April through October), soil moisture is generally between 17 and 27 percent (see Figure 6). Substantial compaction on heavily used skid trails can occur at any moisture content, and likely will be similar in magnitude. Whether this would be the case for skid trails with only a few trips is unknown.

The moisture-density curves illustrate that these Hare Creek soils are very compactible, since 100 percent of maximum relative compaction for the clay loam subsoil (i.e., densities of 1.47 g/cm^3 or greater) was achieved on several of the test plots measured with the nuclear probe. The overall average was 93 percent of maximum. The densities documented here are high for forest soils, but they do not appear to be an artifact of insufficient sampling, deep excavation, or high stone content. Apparently due to texture and clay mineralogy, the soils in western Mendocino County are quite compactible. Therefore, strategies to limit skid trail construction and ameliorate the compaction that does occur are important here.

Soil Tillage Tests

To reduce the impacts of ground skidding on forest soils, heavily compacted areas may be restored through tillage. Concern over reductions in site productivity has caused many private and federal forest managers in the Pacific Northwest and California to rehabilitate the soil in skid trails and landings (Andrus and Froehlich 1983). Several of the tools commonly used for this work were not designed for forest soil tillage. These include brush blades, rock rippers and disk harrows. Winged subsoilers were specifically made for this task.

In the James Creek sale areas, we tested the effectiveness of rock rippers for tillage. Excavation of three cross-sections in JC 82 showed that 39 percent of the soil in the surface 18 inches had been loosened with the five-tined ripper (see Figure 7). Similar results with rock rippers has been documented elsewhere. Andrus (1982) reported that these rippers produce variable success rates in Oregon. He found they fractured 18 to 43 percent of the compacted layer with one pass, and typically created narrow V-shaped trenches. Froehlich and McNabb (1983) state that rock rippers are not very effective on fine textured soils, with shattering occurring on less than 50% of the compacted soil volume.

Further testing of five-tined rock rippers was done in Unit A of JC 83. Part of the unit was tilled under very dry conditions; the remainder was done after minor rainfall had occurred. Observation of this unit and soil density measurements taken after tillage show that effective tillage did not occur here. Density measurements taken one year after tillage were actually slightly higher than before tillage (1.54 g/cm^3 vs. 1.49 g/cm^3).

Several reasons for such poor results in JC 83 are apparent. The D6-D crawler tractor did not have sufficient power to penetrate the rock rippers to 18 inches on the steep, rocky, often excavated primary trails where most of the plots were located. Secondary lateral trails, which were often nearly level, were more effectively tilled. Larger crawler tractors with 200 horsepower or more are needed to till steep trails. Since the compacted layer was not broken up well on the steep primary trails, erosion occurred and carried much of the loose soil that lay above the compacted layer down to landings below. Runoff became channelized in the V-shaped slots carved by the tines, since waterbars were not initially installed. Some of the density plots were located in these eroded reaches. Skid trails undergoing tillage with slopes greater than 20 percent should be waterbarred to prevent soil erosion. Short untilled stretches about every 100 feet can be used instead of conventional waterbars to force water to the surface and off the trail, avoiding gullying (Poff, pers. comm.).

Tillage experiments continued in the HC 86 Timber Sale. The winged subsoiler was tested in both Units A and C, with control plots left untilled. Density measurements averaged 1.23 g/cm^3 after tillage, compared to 1.38 g/cm^3 prior to loosening. Paired t-tests run with the plots showed this 11 percent reduction in density to be significant at the 0.05 level. Density averaged 1.39 g/cm^3 on the untilled control plots in 1988. Excavation of six cross sections in the units showed that 51 percent of the top 18 inches was loosened with this tool. Work in Oregon by Froehlich and Miles (1984) produced fracturing of the compacted layer with the subsoiler in excess of 80 percent on two sites.

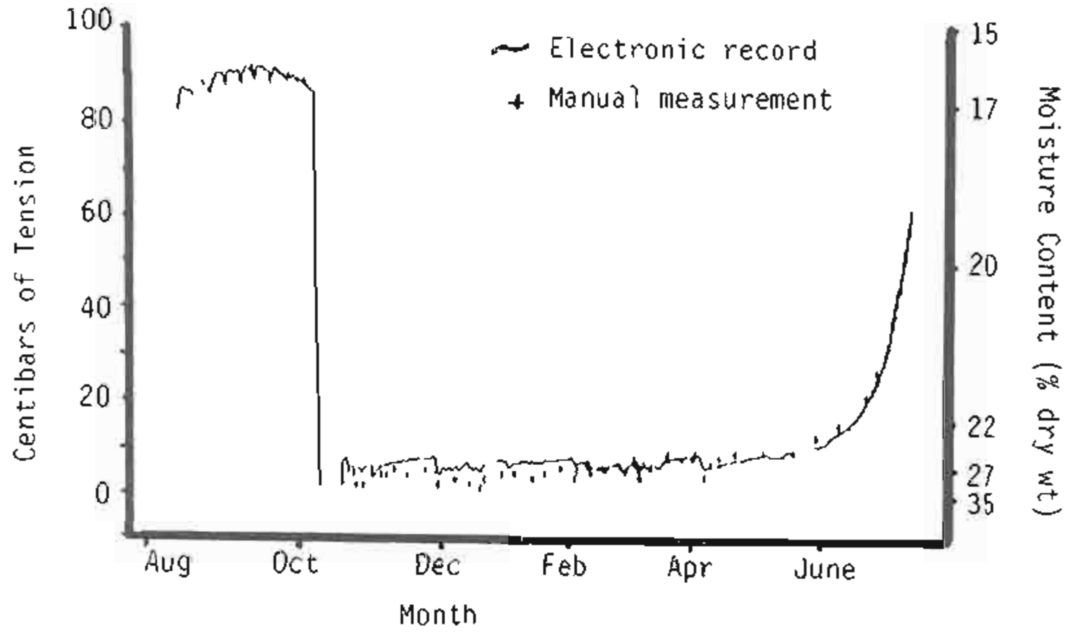
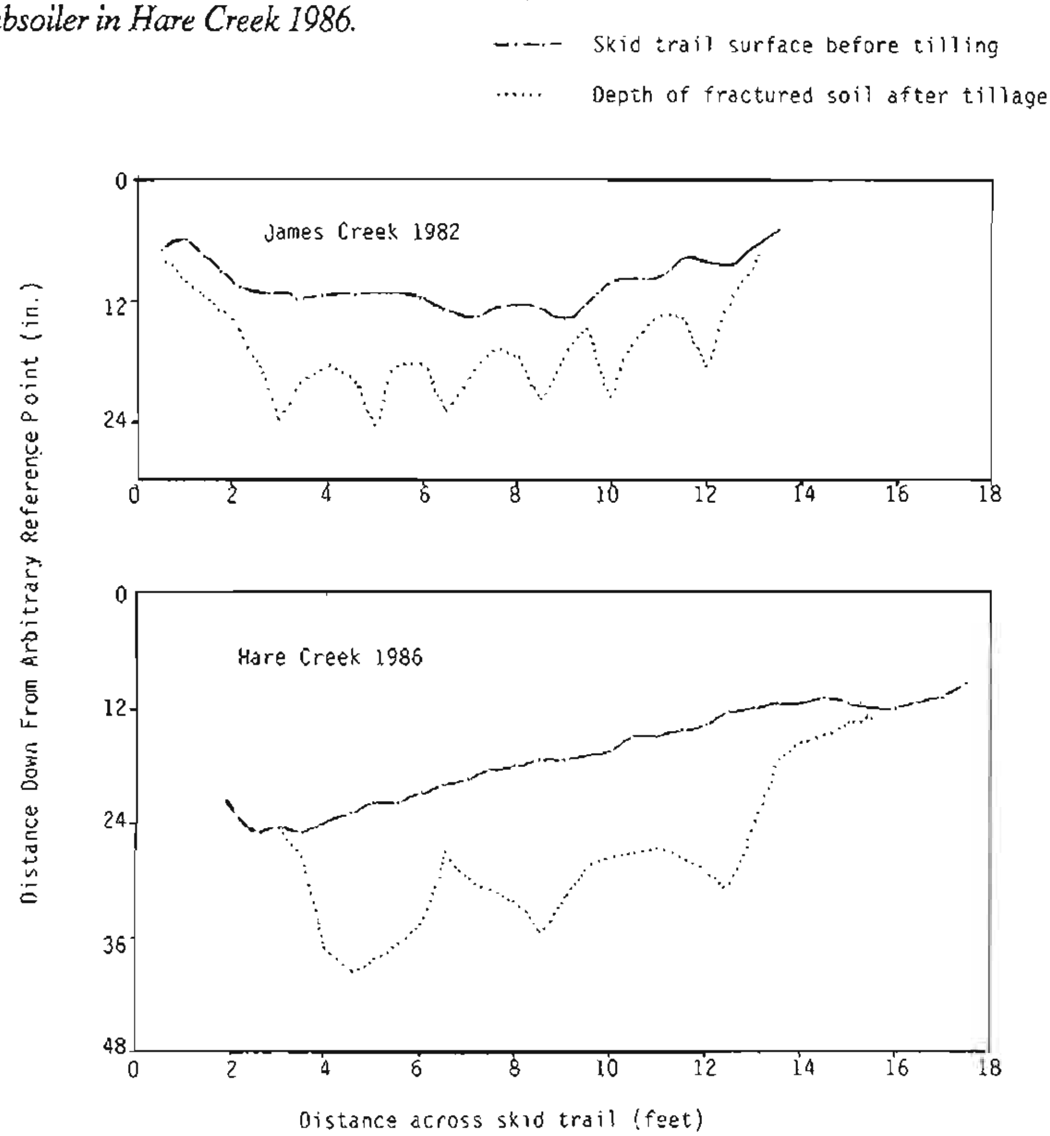


Figure 6. Measurements of soil tension at a depth of 24 inches from August 1988 to the end of July 1989. The corresponding moisture content is also shown. Soil type is the same as that found in the Hare Creek study area.

Figure 7. Excavated cross sections for a rock ripper in James Creek 1982 and a winged subsoiler in Hare Creek 1986.



There are several reasons for our lower fracture percentage. Using the dolly to attach the subsoiler to our tractor meant that the self-drafting feature of the device was utilized only about half the time. At other times, it was tilling too high in the soil profile. Also, we only tried one wing design. It is likely that another pattern may have performed better in this heavily compacted, clayey soil.

The winged subsoiler is clearly a superior tool for skid trail and landing tillage when compared to conventional rock rippers. The lifting and shattering that occurs with the subsoiler is very evident with casual observation. It also can be used to reduce compaction from site preparation work. Davis (1989) reported that soil densities in the Western Oregon Coast Range were 13 percent lower for areas tilled by winged subsoilers when compared with areas where slash had been tractor piled. No significant difference existed between undisturbed areas and areas that were machine piled and tilled.

Even with this tool, however, compacted clayey soils do not respond as well to tillage as coarser-textured soils. Winged subsoilers leave a broad U-shaped shattering pattern, with compacted soil left between troughs (see Figure 7). Also, the soil tends to break into persistent clods. This was very evident in Hare Creek. Andrus and Froehlich (1983) found the clods to last until a second season of rain. The clods make it difficult to interpret density measurements made with nuclear gauges, due to the large void spaces created.

Winged subsoilers are still relatively scarce on the west coast of the United States, while rock rippers are common. If the subsoiler is not available, rock rippers have been shown to be effective on relatively flat skid trails where excavation has not occurred and the A horizon remains intact on industrial forest lands in Oregon and Washington (S. Cafferata, per. comm.). Operation will be most effective in dry granular soils, and soils with higher clay contents may require the operator to make a second pass with the ripper.

Seedling Growth in Skid Trails

After two growing seasons in HC 86 Unit C, the following average heights were obtained for planted redwood container seedlings that were not browsed: uncompacted soil transects -13.in.; tilled skid trail transects -13.2 in.; and compacted skid trail transects -11.8 in. The 18 percent increase in soil density measured in the Hare Creek skid trails corresponds to a 13 percent decrease in seedling height growth. Tilling the trails resulted in a 12 percent increase in height growth. These results correspond closely with those reported by Froehlich and McNabb (1983). They reported nearly a linear decrease in seedling height growth with increasing soil density. However, none of these averages is significantly different from the others at the 0.05 level, due to the small sample size and relatively high variability.

There may be reasons other than soil compaction that may be partly responsible for these height results. The untilled trail is excavated for part of the transect, while the tilled trail is not. Additionally, in both the tilled and compacted skid trail transects, competition from competing vegetation is still minimal. In the undisturbed transects, heavy competition is readily apparent. Since this unit was broadcast burned, ceanothus and manzanita have become significant components of the newly established ground cover. Also huckleberry and sprouting redwoods from cut stumps are major competitors. Redwood sprouts after two growing seasons averaged about seven feet in height. Small redwood plug stock often does not grow rapidly immediately after planting, if their roots are competing for moisture with other plants. Several years may be required for a sufficient root mass to develop to allow significant height growth. By the time growth does occur, the competing vegetation may have already outdistanced the planted seedlings.

Previously, Woodward (1986) measured natural regeneration on and off skid trails created during partial harvesting done in 1975 in another part of the Hare Creek drainage. He found more seedlings on skid trails, but in general they were shorter than those off skid trails. Specifically, seven years after logging, redwood seedling density was 1.5 times, and Douglas-fir was 4.0 times, greater on skid roads than off skid roads. In total, skid trails covered about 9 percent of the area harvested and contained about 21 percent of the conifer regeneration. Redwood seedlings averaged 9 in. on skid trails compared to 44 in. for trees off the compacted areas. The latter heights may be somewhat inflated by erroneously including some sprouts from buried pieces of logs. The grand fir on the skid trails were also significantly shorter than those off (11 vs. 22 in.). The Douglas-fir showed no difference in height (13 in. in both cases), perhaps due to browsing or limited light conditions.

Less definitive results were obtained from the seedlings sampled in the JC 83 skid trails. Measurements made of planted seedlings and naturally seeded trees here produced the results displayed in Table 2. After four growing seasons, significant differences in height did not exist between the trees planted on compacted and tilled skid trails. No sampling was done on undisturbed soil, due to the existing cover on the site.

Heavy browsing has occurred on these seedlings; almost half the trees

Table 2. James Creek 1983: Planted and natural seedling heights on skid trails (data set includes browsed trees).

	Planted ht. (in)		:	Natural ht. (in)	
	Redwood	Doug-fir	:	Redwood	Doug-fir
Tilled - 1985	7.6	13.1	:	---	---
Untilled - 1985	7.8	11.8	:	---	---
Tilled - 1989	12.7	19.8	:	3.0	6.4
Untilled - 1989	12.8	17.4	:	3.9	7.5

(48 percent) were impacted by deer after the first season (see Figure 8). Height averages without the trees judged to be recently browsed in 1989 (43 percent) are still nearly equal to the averages presented in Table 2. It is likely that browsing occurred on many of the other trees in the intervening years, as well. Since the unit has a heavy understory of small trees and brush due to past harvesting, deer use the skid trails as corridors for travel. Eventually, many of the trees will grow sufficiently tall to avoid annual top browsing. Since so many of the trees were browsed, the values presented in Table 2 are not a reliable indicator of soil conditions.

In addition to dense, compacted soil and heavy browsing, the extremely small average growth rate (1 to 2 inches per year) observed here also can be partly explained by the deep excavation that occurred on some of these skid trails. Average cut-bank height of the trails was 4 feet in Unit A's plots and 3.5 feet in Unit C. About one-third of the plots were on skid trails which were not deeply excavated. Clearly, excavating to a lower quality subsoil, or even parent material in many cases, greatly reduced seedling growth on the James Creek plots.

By 1989, Unit A had 48 natural seedlings on 24 plots (41 were Douglas-fir and 7 were redwood); Unit C had 50 natural seedlings on 22 plots (49 were Douglas-fir and 1 was a redwood). Therefore, the average was about two naturals established in each 25-foot plot in five years.

Based on observations made in both the Hare Creek and James Creek units, certain general conclusions can be stated in regard to seedling growth on skid trails. The trees planted on the outside of compacted skid trails, where a berm of fairly loose soil has resulted from excavation on steeper slopes, are growing at much faster rates than those planted in the center of untilled trails. Also, browsing and competition from sprouting redwoods and brush can complicate documenting the benefits of skid trail tillage when typical paired comparisons are made. From this limited sampling, however, it appears that trees planted in skid trails tilled with the winged subsoiler have the best chance of growing at the same rate as seedlings planted on undisturbed soils.

Figure 8. Heavily browsed redwood seedling in an untilled James Creek 1983 skid trail.

MANAGEMENT RECOMMENDATIONS

The results presented in this paper on soil compaction in the redwood region are similar to those reported for many other parts of the United States. Therefore, recommendations that previous researchers have made to reduce potential impacts are applicable here as well. Briefly stated, they are as follows:

1) Limit crawler tractor yarding to slopes of 40 percent or less. Construction of skid trails on steeper slopes, such as those studied on the James Creek sites, removes the A horizon (and possibly the B as well) and compacts the subsoil. This leads to much higher erosion rates (Rice and Datzman 1981). Usually the expense of excavation on ground steeper than this makes cable yarding more cost-effective than ground skidding (Froehlich, pers. comm.). Cable yarding should be done on all slopes where the ground will allow this type of harvesting.

2) Limit the number of skid tails to a minimum. Require skid trails to be at least 100 feet apart, keeping the land base impacted to about 12 percent. Pre-flag trails, review the routes with experienced loggers,

pre-fell the trails, and pre-build the trails. Supervise the loggers to make sure that they are keeping their equipment on these routes, particularly on flatter ground. When contracts are involved with selling standing timber, put language in the document to require adequate trail spacing. Educate loggers so they know why these requirements are being utilized.

3) Avoid winter tractor operations in areas that do not have a cushioning snowpack. While absolute bulk density levels on primary skid trails may be similar to those produced during summer periods for some types of soils, greater soil disturbance occurs. In addition, the risk of accelerated soil erosion and degradation of water quality in nearby streams is usually unacceptable. Puddling resulting from operations on very wet soils is undesirable and should always be prevented.

4) Where uneven-aged management is being practiced, consider the skid trail system to be part of the permanent transportation network, and thus not planted. Entries for each cutting cycle will commonly be frequent (e.g., 5 to 20 years). For even-aged management, consider tilling skid trails with winged subsoilers, particularly if there is a heavy clay B horizon and the A horizon is still present. Clearcutting in the redwood region generally means that a given unit will not be entered again for at least 50 years. Therefore, about 12 percent of the land base, and perhaps considerably more on flat ground in unsupervised situations, will be compacted to the level where growth reductions may occur for the life of the stand.

Whether the economic benefits of increased tree growth will justify the expense of tillage at the start of the rotation has not been addressed here. Stewart et al. (1988) created a model that examined this question, and they state that tillage does appear to be cost-effective under extreme compaction conditions. The cost of tillage, compounded over the length of the rotation, should be less than the value of the growth increase obtained from the treatment. Andrus and Froehlich (1983) estimated the cost of tillage with rock rippers at $101 per tilled acre and $131 per acre for the winged subsoiler. Adjustments for inflation would have to be made for a current cost estimate.

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