THE IMPACT OF EVEN-AGE FOREST MANAGEMENT ON PHYSICAL PROPERTIES OF SOILS

Henry A. Froehlich
Associate Professor of Forest Engineering
Oregon State University
Corvallis

Management of today's forests at almost any level of intensity implies the extensive use of machinery, not only for the initial harvest or stand conversion but for the application of a variety of silvicultural treatments as well. The equipment has the potential for markedly modifying the physical properties of the surface soil layers, which may significantly affect regeneration and future growth. Some form of crawler tractor or rubber-tired skidder is the primary machine used in all but the steepest regions of North American forests. Throughout the West, loggers commonly use crawler tractors or rubber-tired skidders on slopes up to 30 or 40 percent and occasionally on slopes up to 60 percent. Recently, the Forest Industries magazine reported on a rubber-tired skidder being used on slopes up to 84 percent. This is probably the exception, as most slopes above 40 percent supporting old-growth timber in the West have been harvested by some cable system, such as conventional high-lead or skyline methods. Until very recently, young-growth forests have been thinned almost exclusively by crawler tractors and skidders adapted from equipment used in harvesting old-growth timber. Now, loggers are beginning to develop cable systems for thinning and harvesting in young-growth stands.

The change in the properties of the surface soils as a result of harvesting and thinning may be either beneficial or harmful. Some degree of exposure of mineral soil is frequently desired as an aid to regeneration. Beyond the soil disturbance from scarification by dragged logs or machine movement, there is often a much deeper disturbance from the construction of tractor trails. This becomes especially visible as the slopes approach the maximum for the operation of ground-based equipment. Another type of disturbance that is less visible is soil compaction in the routes used for machine and log movement. The areal extent of the surface disturbance and even the degree of compaction may be measured easily. The actual effect that this has on tree or stand growth over a rotation is not so readily observed and many unanswered questions remain on the subject.

FOREST SOIL CHARACTERISTICS

It is impossible within the scope of this paper to attempt to characterize the ideal soil system for each commercial forest species. Some things can be said that generally identify the highest producing sites, however. The significance of permeability, texture, and available moisture in influencing tree growth is recorded by research in forested areas around North America (1, 2, 4, 15, 35). Lutz (17) states that the critical apparent density varies with texture, and, "Optimum compactness is that apparent density at which the particular soil has the pore-size distribution that will give the water and air capacity and movement best suited for plant growth." The natural bulk density of high-site forest soils is generally quite low, normally increasing with depth. Expressed as bulk density, the surface layers of many productive soils are reported to have densities ranging from about 0.5 g/cc to 0.9 g/cc. Schlots, Lloyd, and Deardorff (29) provide detailed descriptions of 14 Douglas-fir soils in western Washington. The highest site-index values are on those soils with a porosity that permits free permeability of air and moisture throughout the profile. Forristall and Gessel (8) indicate that effective rooting depth is related to soil density and soil porosity and that the lower limit of the effective rooting depth corresponds to a marked increase in bulk density. Lutz' concept of an optimum compactness is supported by Steinbrenner's (31) findings on the relation of macroscopic pore space in the B horizon to site index of Douglas-fir in western Washington. He found that from a lower reading of 7 percent there is an increase in site with an increase in macroporosity up to 14 percent, followed by a decrease in site with an increase in pore space beyond this.

Thomas, Pomerning, and Simonson (38) provide a range of values for the particle size distribution for a large number of soil series found in Oregon as well as the site class for Douglas-fir commonly associated with these soil series. The most productive soils are found to be associated closely with a clay content of about 20 to 35 percent, with generally a wide range of particle sizes for the balance. For these soils to have the generally low bulk density and high porosity found under undisturbed conditions, a high degree of aggregation must be present. The loose, friable nature of these soils under natural conditions is the result of chemical and physical weathering and biological activity. Freezing-thawing, drying-wetting, root growth and decay, and the activity of micro- and macroscopic soil organisms have all played a part in forming the surface layers of soil into aggregates of mineral and organic material to provide a medium in which soil-water solutions may move relatively freely and adequate aeration may occur. Mechanical impedance of the coarse lateral and fine feeder roots under natural conditions is at a minimum. It is understandable that soils of this type would be readily subject to changes during logging.

THE COMPACTION PROCESS

A brief look at some of the equipment currently in use shows that many of the rubber-tired skidders weighing between 10,000 and 18,000 pounds have a rear-wheel ground pressure of from 20 to 28 lb/in^2. This would be static pressure at the rear wheel with the machine holding a normal turn of logs. Crawler-type tractors may range from about 10,000 to 36,000 lb or more, with ground pressures ranging from 6 to 13 lb/in^2 assuming equal distribution of weight over the whole track-bearing surface. Some logging equipment now under development is expected to have ground pressures of near 4 lb/in^2. These values of ground pressure are for static conditions of the fully equipped but unloaded tractors. The effect of the various sizes of loads, bouncing action, and vibration when the machine is in motion all add to this minimum, and the actual ground pressures may be increased several times.

Both vertical pressure and vibration change the physical condition of the soil. Any pressure on the soil surface greater than the natural internal friction will cause the aggregates to shift relative to each other and thus initially reduce the macroscopic pore space but basically retaining the aggregate units. With further pressure, plastic deformation will occur at contact points between the aggregates. Repeated trips over a soil surface also produce a kneading action that alternates the direction of pressure in a soil unit, thus accentuating compaction. Continued or repeated pressure and vibration in the presence of a sufficient moisture to lubricate shear planes within and between aggregates will cause puddled soils, a severe breakdown of the soil structure (20). Chancellor, Vomocil, and Aerf (3) provide a detailed sequence of soil change from compaction in their study of energy disposition in compression of agricultural soils.

A standard engineering test commonly used to determine the optimum moisture content for maximum soil compaction will help to visualize the influence of moisture in decreasing the shear strength. In this test, the selected soil is confined in a cylinder and subjected to a known compactive effort. The test is run at several increments of soil moisture with the results plotted as a curve from which the optimum moisture content may be read. An example of the type of curve produced by a clay loam forest soil is shown in Figure 1.

In this example, 95 percent of the maximum compaction occurs at a moisture content ranging from 14 to 30 percent. The absolute value of dry density would be somewhat higher were it not for the high organic matter content of the surface soils. Note that below the optimum moisture content, further compaction could be produced with a greater compactive effort. Above the optimum moisture level, the excess pore water pressure effectively limits the density that can be attained under the test conditions. Under unconfined conditions, however, the soil will become plastic enough to flow away from the compactive force with a rapid loss in soil structure. A soil with a wide range of particle sizes may be compacted to a greater density than more uniform soils and will compact at a lower

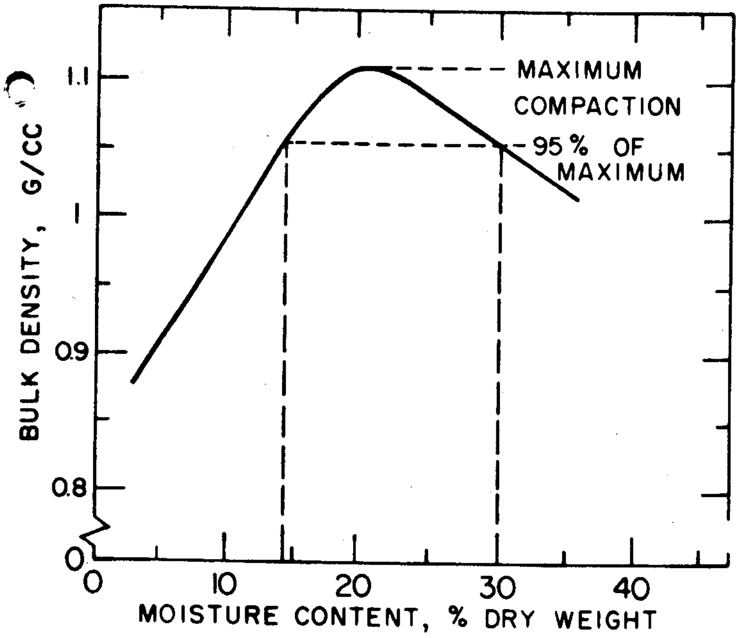

Figure 1. An example of the results from the Proctor Test of the surface layer of a clay loam forest soil.

moisture content. Sandy clays, for example, may be compacted to densities of 1.7 to 2.1 g/cc at only 8- to 15-percent soil moisture, but the maximum densities of clays are in the range of 1.5 to 1.7 g/cc achieved at 20- to 30-percent soil moisture. Of course, these maximum densities seldom are achieved under field conditions. The Corps of Engineers, Waterways Experiment Station (40), reports that this optimum moisture content for compaction occurs about midway between soil moisture tensions of 0.06 and 15 atmospheres, approximating field capacity and wilting percentage. This general rule appears to be realistic for soils ranging from clays to sandy loams.

The degree of soil compaction actually achieved is thus strongly related to the moisture content, degree of aggregation, and organic content. Day and Holmgren (5) aptly described the soil reaction to pressure:

> During compression the forces exerted upon an individual soil aggregate by the surrounding aggregates comprise a complicated force system. The factors which determine the shearing strength are the internal cohesive forces and the friction forces. Plastic deformation can be expected only if the applied stress is sufficiently great to overcome the shearing strength; otherwise, the aggregate will function as a mechanically stable structural unit. This principle is a necessary starting point in the interpretation of soil compression.

These authors also demonstrate the effect of changes of moisture content and three levels of pressure on bulk density of a silty clay loam (Table 1). Thus at about 25-percent moisture content, a pressure of 14 lb/in^2 increased bulk density by 64 percent, but, at about 15-percent moisture, a comparable pressure only increased bulk density by 27 percent.

Table 1. Relation of Moisture Content and Pressure to the Bulk Density of a Silty Loam (5).

Water content	Initial	Final
%	*G/cc*	*G/cc*
7 lb/in.^{2}		
25.3	0.78	1.23
15.4	0.78	0.93
14 lb/in.^{2}		
25.4	0.81	1.33
15.3	0.78	0.99
21 lb/in.^{2}		
25.4	0.84	1.69
15.5	0.78	1.07

PHYSICAL CHANGES IN SOIL PRODUCED BY HARVESTING AND THINNING

Density, Porosity, and Infiltration

It is impossible to make a direct comparison of the laboratory compaction tests to the compaction produced in the field. That is, the energy applied in the Proctor test may not be duplicated by the tire or tread of a harvesting machine. The test should serve as a good index of what can occur under field conditions, however. Steinbrenner and Gessel (34) observed a 35-percent increase in bulk density on tractor skidroads after six trips with a tractor under winter conditions on a silty clay loam (Olympic series). Soil density increased about 17 percent after six trips under summer conditions, and it required about seven or eight trips to achieve a 35-percent increase in density under summer conditions. Weaver and Jamison (41) indicate that the first four passes of a tractor produced the greatest increase in density in the agricultural soils of their study. My observations on tractor thinning of areas on a reddish brown clay (Nekia series) indicate a 25-percent increase in bulk density between the logged areas and the heavily disturbed areas. The change in density is related almost directly to the loss in macroscopic pore space, and this loss in pore space markedly influences permeability and infiltration.

Steinbrenner and Gessel (33) found that tractor-cutover land had a 2.4-percent increase in bulk density, a 35-percent loss in permeability, and a 10-percent decrease in macroscopic pore space compared to undisturbed soils. Skid trails in the same area showed a 53-percent loss in macroscopic pore space and a 93-percent loss in permeability. Steinbrenner (30) found that, although it took six trips with the tractor to reach maximum compaction, nearly all of the loss in infiltration rates occured with the first two trips. It required about four trips in summer to achieve the same loss in infiltration. Dyrness (6) noted that undisturbed forest soils in his study on the Andrews Experimental Forest in the Oregon Cascades had about 77-percent pore space, but compacted soils in adjacent tractor logging averaged about 63 percent. This change in pore space was brought about by a change in bulk density from 0.603 g/cc in the undisturbed areas to 0.975 g/cc in the compacted areas of tractor logging.

Perry (27) studied the soil conditions under loblolly pine 26 years after planting. He found that infiltration for a given quantity of water required 3.5 min in planted fields and 18.5 min in areas compacted at the time of planting. On currently compacted sites the infiltration time ranged from 80 min to more than 4 hr. Trimble and Weitzman (39) found that it took 619 times longer for a given quantity of water to enter the soil of a skidroad than to enter the A-horizon of an undisturbed forest soil, and 20 times longer than to enter into the B-horizon. Munns (23) found that infiltration was reduced by 75 percent on tractor-logged sites in the pine region of California, and Hulisashvili (14) observed that after clearcutting of a pine-spruce-oak forest on brown forest soils of the eastern Georgia regions of the Soviet Union there was about 50 percent less noncapillary pore space. This loss in large pore space gave rise to a 3.5-fold decrease in infiltration.

Depth of Compaction

The depth to which the compaction is found is quite variable. It penetrates deeper under wet soil conditions than under dry, and the more porous the soil initially the greater the compaction depth. Munns (23) found that compaction under tractor logging with relatively light equipment in the pine region of California penetrated to at least 10 in. in depth. Lull (16) reviewed a number of studies that show compaction depths from 6 to 24 in. He concludes that the depth to which compaction occurs does not generally extend beyond 12 in. below the bearing surface and that laterally the effect is limited to 12 to 18 in. from the tire or tread. It is difficult to relate compaction on agricultural soils to that occurring in logging, because the latter is produced by a combination of tire or tread pressure, kneading action, and vibration from the equipment plus the pressure and scarification from the turn of logs.

Areal Extent of Soil Disturbance

As early as 1947, Munns (23) raised the question of possible damage to soils when he observed that tractor trails and roads covered from 25 to 40 percent of a logged area in the pine region of California. Steinbrenner (30) reported that 26 percent of a tractor-logged area was occupied by tractor skidroads and included deep displacement of soil, surface compaction, and puddling of saturated soils. Dyrness (6) also found that although up to two-thirds of a tractor-logged area may be disturbed during logging, about 26 percent of the area may be classified as compacted. His report also shows that high-lead cable logging during clearcutting produced about 9-percent surface soil compaction.

Wooldridge (42) compared the soil disturbance produced by partial cutting with tractor logging and a skyline crane system. He reports that deep soil disturbance occurs on about 16 percent of the tractor logging and only 3.2 percent under the skyline crane method. Haupt (13) observed that partial cutting of old-growth ponderosa pine produced soil disturbance ranging from 3 to 18 percent, varying with the initial stand volume, volume removed, and size of equipment. My observations of several thinnings in 50- to 90-year-old Douglas-fir lead me to expect that from 40 to 60 percent of the thinned sites will be disturbed, with from 20 to 30 percent of the area having heavy disturbance and compaction.

EFFECT ON SEEDLING AND TREE GROWTH

The literature on the effect of compaction on agricultural crops is quite extensive, but that dealing with forest crops is limited. The effect of compaction on tree roots has centered around three factors; physical impedence, gaseous exchange, and nutrient and moisture movement (28). Zimmerman and Kardos (44) found that root penetration is correlated negatively with bulk density, but that there is a wide difference between plant species in ability to penetrate dense soils. Forristall and Gessel (8) noted that in Alderwood gravelly loam, Douglas-fir and western hemlock root growth is restricted significantly when the bulk density approaches 1.25 g/cc. Minore, Smith, and Woollard (21) observed the effects of high soil density on seedling root growth of seven northwestern tree species. Soil columns were compacted to 1.32, 1.45, and 1.59 g/cc and seedlings allowed to grow for 2 years under greenhouse conditions. The roots of all seven species grew through the 1.32-density soil cores. The roots of western redcedar, Sitka spruce, and western hemlock did not penetrate 1.45-density cores, but roots of red alder, lodgepole pine, and Douglas-fir grew through them. No roots penetrated the 1.59-density cores. Steinbrenner (31) observed that no roots were found in soil layers that preclude passage of air at 15 lb/in^2. Pearson and Marsh (25) found that the compaction of certain soils in the Black Hills region had an unfavorable effect on the reproduction of ponderosa pine because the altered soil structure impeded root development. The undesirable characteristics were accentuated by logging operations in wet weather. Steinbrenner (32) noted that plants on the skid trails tended to have shallow root systems brought about by the reduction in natural macroscopic pore space, lower permeability, and reduced oxygen capacity of the soil. Sutton (36) reviewed a number of papers on the form and development of conifer root systems and concluded that roots will grow only in that part of the soil where moisture, aeration, and mechanical properties are favorable. Aeration has been shown to influence total root surface area, size of root-hair zone, and fibrousness in roots of several species. Pearse (26), working with Douglas-fir and western hemlock grown in sandy loam compacted to densities of 0.59, 0.84 and 1.02 g/cc, found that total root length after 8 weeks was least in the most compact soil.

Hatchell, Ralston, and Foil (11), working with loblolly pine, also found that root weight was correlated negatively with bulk density over a range in density from 0.8 to 1.4 g/cc. Shoot-root ratio was correlated positively with noncapillary porosity and oxygen diffusion rate. Foil and Ralston (7) reported that compaction of a variety of soils, whether at 3.5 or 10.5 kg/cm^2 of surface pressure, greatly reduced size and weight of loblolly pine seedlings. Small differences in growth among compaction treatments indicated that even the smallest pressure applied reduced soil aeration and increased mechanical impedence to root growth to unfavorable levels. Some height growth effects were observed on first-year growth of loblolly pine. On one area, there was a small but statistically nonsignificant height-growth difference between seedlings on a secondary skid trail and an undisturbed area. On a second area however, seedlings averaged 3.8 in. on a primary skid trail, compared to 4.8 in. on an undisturbed site. On primary skid trails there was a 43-percent loss in seedling height growth on the first site and a 53-percent loss on the second site.

Youngberg (43) measured the influence of soil conditions after tractor logging on planted Douglas-fir seedlings. He showed that the average leader growth in the cutover area was 6.8 in., compared to 5.3 in. for seedlings growing on a tractor trail berm and 3.9 in. for seedlings growing on a heavily disturbed tractor trail, a 43-percent reduction from those in the cutover area. The Bureau of Land Management, Eugene District, reported a 57-percent loss in terminal leader growth between undisturbed sites and tractor skidroads on 8-year-old Douglas-fir seedlings.[1] Their data also indicate the relation of bulk density to leader growth (Table 2).

Table 2. The Effect of Bulk Density on Leader Growth[1].

Bulk density	Leader growth
G/cc	*Inches*
0.84	26.69 ± 5.95[2]
0.94	23.71 ± 4.62
1.06	22.88 ± 4.70
1.15	18.60 ± 6.39
1.24	17.22 ± 7.79

[1]From unpublished paper on file at Bureau of Land Management, Eugene District, Eugene, Oregon.
[2]Plus or minus standard error of the mean.

Actual values for effects on residual tree growth seldom have been reported. Olson (24) described a "logging shock" that results in considerable loss of trees and arrested growth in residual stands of western white pine. Perry (27) measured growth on loblolly pine 26 years after they were planted. Data from 30 pairs of trees showed a significant reduction in growth between trees growing on compacted areas and those in surrounding fields (Table 3).

Table 3. Average Growth of Trees in Compacted and Uncompacted Areas (27).

Location	Dbh	Height	Volume
	In.	*Ft*	*Cu ft*
Woods road	6.3	54	4.1
Surrounding fields	8.7	62	8.8

In an effort to determine the combined effect of tractor and load on soils and tree growth, Moehring and Rawls (22) selected a series of loblolly pines in a 40-year-old stand. The soil was compacted by a small tractor pulling a load of three 10-foot logs passing six times near the tree. The treatment was applied during wet weather, and the results were measured in terms of growth 5 years later. Growth was found to be affected only slightly when compaction was limited to one side of a tree. Compaction on two, three, and four sides of a tree produced 13.7, 36.3, and 43.4 percent less volume over the 5-year period.

PERSISTENCE OF COMPACTED CONDITION

The longevity of the compacted condition is of major interest to forest managers, but data on rates of recovery still are limited. Of course, the same forces that were instrumental in bringing about the porous soil structure and aggregation will begin to restore the soils to their natural tilth. The process sometimes may be quite slow, and possibly some threshold or limit exists from which a given soil may recover quickly and beyond which a long interval will be required. Coarse-textured soils apparently will recover more quickly than fine-textured soils. Mace reports on the recovery of a sandy soil after thinning of a 90- to 100-year-old red pine stand in Minnesota. Immediately after thinning, a 5-percent increase in bulk density was determined for the skidder trails used in a tree-length yarding, and an 11-percent increase in bulk density was found in skidder tracks used in skidding full trees. The lightly compacted soils were markedly recovered after one overwintering period. The somewhat heavier compaction produced by the full-tree skidding is recovering at a slower rate. In both, the compaction near 6-inch depth had recovered significantly in 1 year, apparently because freezing and thawing are more prevalent at lower depths in sandy soils and permit a quicker recovery (18, 19).

In western forests, soil freezing appears to be much less prevalent. Hale (9, 10) notes that the forest soils of the high Cascade Mountains, both east and west side, remained unfrozen throughout the winter and spring of 1949-1950. In the following winter, frost occasionally penetrated to 3-inch depth under lodgepole pine stands and about 2 inches under ponderosa pine stands. At no time during the observation were there extensive areas of impermeable frozen ground. In the Coast Range of Oregon and Washington freezing-thawing cycles apprently will not add significantly to natural recovery of soil tilth.

Munns (23) noted little or no change in the infiltration rate within 2 years after logging. Tackle (37) also used infiltration as an index of soil condition on a silty clay loam after logging on western larch and Douglas-fir land in the intermountain region. The relative infiltration values in the first and fifth years after logging are shown in Table 4. The scarified condition listed above indicates that the litter layer was removed or disturbed excessively by the tractor in logging or piling slash. Lutz (17) cites an example of soil compaction from tractor tire pressure in orange groves and noted that the

Table 4. Infiltration Values in the First and Fifth Years After Logging (37).

Condition	1st year	5th year
	%	%
Undisturbed	100	100
Scarified	15.4	48
Broadcast burn	62.5	135[1]
Tractor skidroad	4.1	4.1

[1]Had recovered by 3-4 years.

elimination of cultivation for 8 years and the growing of cover crops partly restored a good physical condition.

AMELIORATION OF COMPACTED CONDITION

Artificial means of loosening the compacted soils may be possible, but the results of such efforts are highly variable. Both the Bureau of Land Management and U. S. Forest Service have required certain compacted areas to be scarified, and Steinbrenner (32) reports that this also has been done on some private forest lands. The success of the scarification projects is not known at this time, but some measure of improvement apparently is achieved. Experience from agricultural soils indicates that the condition of the soil at the time of scarification is crucial and that if the work is done under a moisture content near the optimum for compaction, further compaction may result. Hatchell (12) studied the effect of compaction and loosening treatments on loblolly pine grown in cores of compacted soil and noncompacted soil taken from adjacent sites. A randomly selected portion of each soil condition was loosened to 0-, 3- and 6-in. depths. Loosening was achieved by removing the core and breaking it into particles no larger than 1/4 in. in diameter and then loosely packing the soil into a soil column. The soils in their compacted condition had bulk densities from 1.12 g/cc for a clay loam to 1.62 for a silt loam. The author makes a special note that the greatest retardation in growth on compacted soil as compared to noncompacted soil was observed on silt loam soil. Loosening compacted soils did not produce a significant increase in growth of shoots and roots. Mean dry shoot weights for compacted soils loosened to 0-, 3-, and 6-in. depths were respectively 184, 211, and 207 mg, and respective root weights were 66, 79, and 74 mg; these weights are considerably less than those on noncompacted soils with no loosening–344 mg for shoots and 105 mg for roots. Loosening compacted cores resulted in a percentage of seedling establishment that was almost as high as the percentage on cores of normal soil, however. Longer term studies clearly are needed to learn what effect various loosening or scarification treatments have on restoring desirable soil properties. Mechanical loosening, if done under proper conditions, apparently will at least make it possible for natural forces to act more quickly on the compacted soils.

Some tree species and many other grass and shrub species can penetrate dense soil to a greater extent than some of our desirable commercial species. Perhaps alder, *Ceanothus*, or other pioneer species will serve a useful purpose in this fashion in the Northwest. Lull (16) reviews papers that indicate the beneficial role of mustard, grasses, and legumes in improving infiltration rates. The increasing practice of seeding skid trails and landings with grass species as an erosion-control measure also should be beneficial in speeding the recovery of the compacted soil.

CONCLUSION

The problem of the effect of the harvesting and thinning processes on desirable physical soil properties varies markedly from soil to soil, but at times it can cause a serious loss in seedling establishment, growth, and long-term productivity. Some degree of soil disturbance and compaction is almost inevitable in harvesting, but it may be reduced significantly by the proper selection of equipment and the timing of its use. The combination of a high degree of mechanization utilizing heavy equipment and the naturally porous nature of the most productive soils intensifies the problem. An understanding of the compaction process and the physical nature of the soils we manage will aid in reducing the degree and amount of soil problems from intensive use of machines. The actual physical change is primarily one of reduction of noncapillary pore space, which in turn reduces infiltration, permeability, and gaseous exchange. A smaller, but at times significant, area may be puddled, which represents a severe loss of soil structure. Various studies in old-growth harvesting indicate that from one-quarter to one-third of a clearcut area may be affected seriously by ground-based machines and from 3 to 9 percent of the area may be affected by cable harvesting systems.

Some studies have shown that the effect of compaction on seedling growth varies greatly between soils and with tree species. There is a consistent trend toward a reduction of both seedling root length and shoot or leader growth. Losses in height growth range from 14 to 53 percent depending on soil type, degree of compaction, and tree species. The trend of growth on residual trees affected by compaction also is correlated negatively with density and may range from relatively small reduction to over 40-percent loss in growth on individual trees.

The compaction under some conditions persists for a long time, perhaps at least a few decades and is more persistent in clayey soils than coarse-textured soils. Freezing and thawing and drying and wetting appear to be major agents in restoring soil structure that act most rapidly on the least compacted soils. Mechanical means of loosening compacted soils appear to hold some promise under some conditions but primarily as a means of aiding natural forces to act on the soil mass. Biological means of improving soil conditions are probably more certain, and the use of selected plant species to pioneer the recovery of the affected soil shows considerable promise.

A major question still to be answered is: What is the effect of the disturbance and compaction on a forest stand over a rotation? It may be that those trees in the vicinity of compacted sites may be able to compensate for some loss of rooting space and the release from competition from the disturbed area may still allow accelerated growth. Seedlings or planted stock on the skid trails clearly appear to suffer growth losses, but it has been suggested that those planted adjacent to compacted areas may not suffer serious growth loss if the soil condition is ameliorated by the time the root development of the young stand requires the use of these areas. Because the potential for growth loss appears to be substantial, however, especially under intensive forest management, every effort to minimize the impact is warranted.

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