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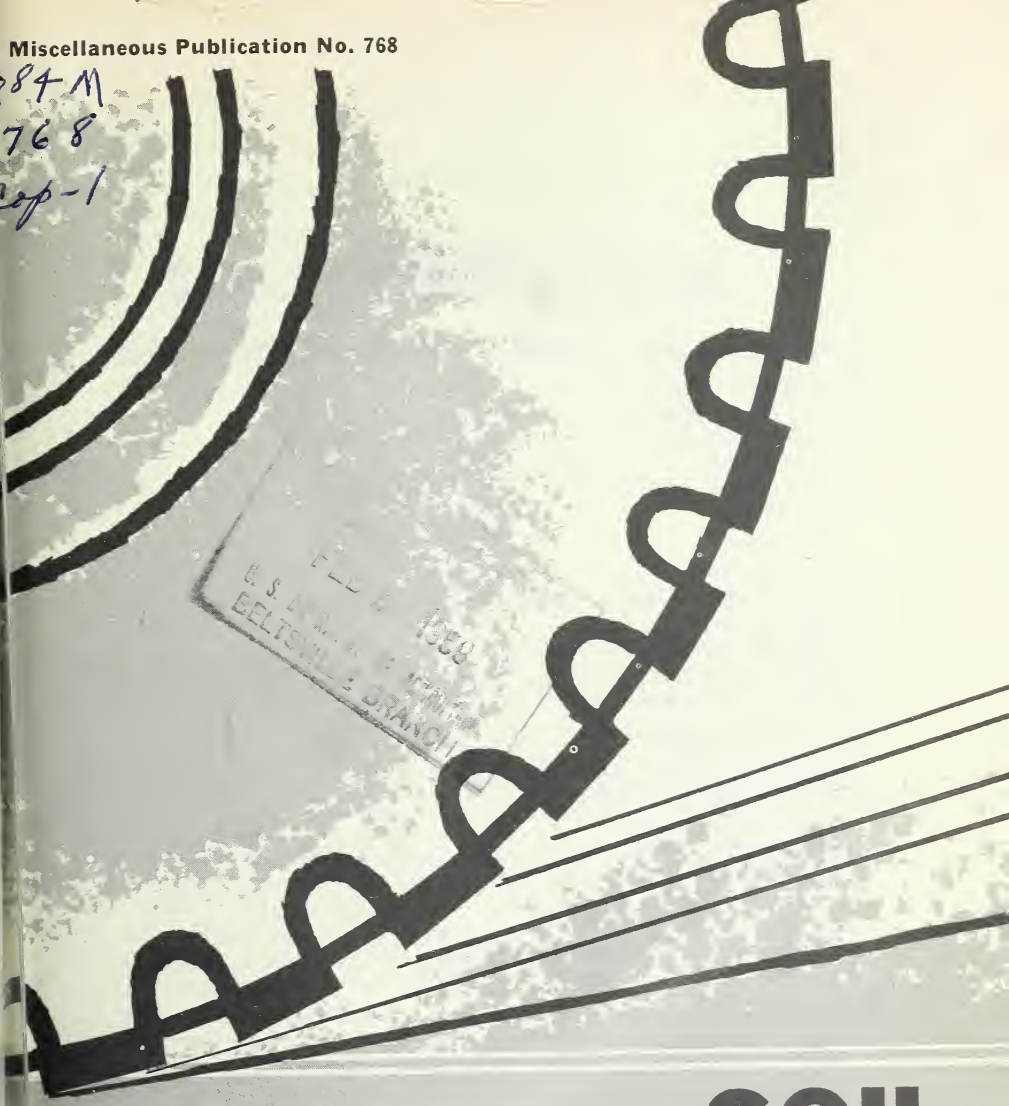

SOIL COMPACTION

On Forest and Range Lands

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SOIL COMPACTION
ON FOREST AND RANGE LANDS

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Introduction

Whenever you put a foot down on forest or range land, you are—to a degree—compacting the soil. The hooves of cattle, the wheels of vehicles, the weight of a dragged log: all these can compact the soil, too. Soil compaction is a common and universal process.

Soil compaction can be defined briefly as the packing together of soil particles by instantaneous forces exerted at the soil surface resulting in an increase in soil density through a decrease in pore space.

Sometimes soil is compacted deliberately to good purpose. For instance, engineers compact soil to improve roadbeds or to build earthen dams; this increases the soil's resistance to further deformation. Seedbeds in forest nurseries are rolled to make the soil more retentive of moisture and to press seed into the soil.

But for purposes of soil and water conservation, compaction is usually harmful. The effect is to increase the density of the soil by reducing pore space. This loss of pore space reduces infiltration capacity, and water movement through the soil is slowed. Then surface runoff may occur more frequently and may increase in volume. Erosion begins; and, once begun, may be difficult to stop.

Undisturbed forest and range soils are highly permeable, compared with cropland, and can be easily deformed by traffic. Once compacted, they are subject to runoff and erosion. And, since large areas of forest and range soils are located on steep mountainous areas subjected to the greatest rainfall intensities and amounts, this can lead to serious problems.

Compaction occurs during the harvesting of forest products by logging, during the harvesting of range forage by the trampling of livestock, and on bare soils from rainfall impact. Forest soils also become denser, without application of compactive forces, when their organic-matter content is reduced. Because the responsible processes do not entail compacting forces, this aspect will not be considered.

The purpose of this report is to review available information on soil compaction as related to soil and water conservation on forest and range lands.

So far, almost all the studies on this subject have dealt with the effects of logging in the Pacific Northwest. Either soil compaction does not occur in other forest regions, it is not a problem, or (more likely) its effects have not been recognized. The dearth of literature on forest soil compaction is equaled by a dearth of information about range soils.

For this report, pertinent information was derived in the main from studies that are not primarily concerned with compaction. For example, a report on areas disturbed by logging provided insight on areas compacted. Similarly, studies of bulk density, pore space, and infiltration relationships offered clues to physical effects of increasing soil density.

Engineering literature on soil mechanics was particularly valuable in describing the compaction process. Though engineers are interested mostly in how to compact the soil so as to increase its supporting strength and reduce permeability, such findings—viewed contrariwise—suggest means of protecting soil from compaction. For instance, engineers have found that maximum compaction of soils of different textures is achieved at rather definite moisture levels, a clear suggestion as to when travel over the soil surface should be avoided to prevent compaction.

This report has three major parts: first, the overall compaction problem as it relates to compaction by logging, trampling, and rainfall impact is discussed; second, the mechanics of the compaction process are described and factors affecting and affected by it are noted; and third, remedies for compaction and methods of controlling it are discussed and summarized.

Discussion of the compactive forces exerted by different types of vehicles cannot at this time be related to the ensuing rearrangement of soil particles and its effect on infiltration, percolation, and surface runoff; this information is not available. Here is presented only some of the available information. A considerable amount of research is necessary to close the obvious gaps.

The Compaction Problem

The more intensively forest and range lands are used, the greater the opportunity for soil compaction. Dirt roads, skidroads, sheep or cattle trails, log decks, and bedding grounds represent compaction at its worst. Compaction of forest soils is becoming more serious as the use of heavy mechanized equipment increases. Though seemingly outside the purview of this report, the extent and effect of cropland compaction may be of interest in that they reveal the maximum effect produced over large areas, some of which in time may revert to forest or range cover.

For instance, Laws *(43)*[1] has reported that crop yields in the Texas blacklands have declined 40 to 50 percent during the last 50 to 100 years. Commercial fertilizers have not materially improved yields, and the decline is believed due to the formation of a compacted layer in the soil as a result of common tillage practices. In irrigated orchards and croplands in California, soil moisture penetration has been restricted by a compacted layer produced by cultural operations *(32)*. After 100 years of farm-implement development, more than half of Germany's cultivated soils are in poor condition—due largely to compaction by tractors *(23)*. In Great Britain, the rapid increase in the weight of tractors in recent years has led to predictions of serious effects on the soil *(19)*.

These dismal prospects may be extended to forest and range soils as they receive more intensive management. Systems of selective or partial cutting call for repeated travel over forest soils, more frequent use of logging equipment, and thus greater opportunity for soil compaction. Some concern has been expressed as to the damaging effects of heavy logging equipment on soils of the Northeast and Northwest *(72, 79)*.

Perhaps in a lesser sense the same situation exists on range lands. Management to increase carrying capacities may also result in greater trampling and compaction. The use of heavy equipment to clear brush from western ranges may have some influence.

[1] Italic numbers in parentheses refer to Literature Cited, page 29.

However, more intensive management of forest and range lands does not always result in greater soil compaction. Protection of the forest from fire, insects, and disease—or any range practices designed to maintain or increase the cover—would tend at least to maintain soil organic materials and thereby soil density. But beneficent effects derived from long-time protection can disappear rapidly under the tractor treads or trampling of a short-term harvesting operation.

Thus, in large measure, whenever timber and forage are removed, the soil is compacted to some degree. The seriousness of the effects has not been carefully evaluated. They may even have been overlooked. For instance, in the numerous studies of the effects of land use on runoff and erosion, the influence of soil compaction has been neglected. Not unreasonably, some of the great differences in amounts of runoff and erosion that have been frequently recorded, from plots of various types or densities of vegetal cover, may well have been caused by soil compaction during the course of plot treatments. Show-me trips can also provide a perennial means of compaction.

Compaction By Logging

In a logging operation, the extent of compaction depends on the type of equipment, the terrain over which the logs are skidded or hauled, the frequency of travel, and the type of soil and its moisture content.

Type of Equipment

Other things being equal, crawler tractors, compared with wheeled vehicles or horses, compact the soil the least. They exert a ground pressure (pressure at the soil surface) of 3 to 9 pounds per square inch, depending on the weight of vehicle and width and length of track *(34)*. Ground pressures for crawler tractors of different weights are as follows:

	Standard track		Wide track	
Tractor weight (pounds):	*Standard length (pounds per square inch)*	*Extended length (pounds per square inch)*	*Standard length (pounds per square inch)*	*Extended length (pounds per square inch)*
40,575	8.82	7.86	6.93	6.18
18,170	7.24	6.36	4.83	4.24
10,930	6.66	5.76	3.61	3.12
7,570	5.41	4.49	3.25	2.69

Pressures are reduced substantially by using wide, extended tracks. In order of increasing weight, width of trails made by the above four tractors are 9, 10, 11, and 12 feet.

Ground pressures from wheeled vehicles are considerably greater. Compared with an assumed average ground pressure of 7 pounds per square inch for crawler tractors, pressures of agricultural tractors may average around 20 pounds, passenger cars 30 pounds, and trucks 50 to 100 pounds per square inch. Horses may exert a pressure of about 40 pounds per square inch *(5)*.

To reduce road construction costs and distance of crawler-tractor skidding, wheeled tractors are being employed in some regions to move logs from places where crawler-tractors bunch them to places where trucks can get them economically. Tire inflation pressures of current models are about 50 pounds; in future models the pressure will be about 30 pounds *(93)*.

Though crawler-tractor pressures are not so great as those of other types of vehicles, their compactive effect may be proportionately greater by reason of the greater area of soil subjected to mechanical vibration. Huberty *(32)* has pointed out that even when the weight of power equipment is not great, vibration of the

soil must play an important role in soil compaction, especially when the soil contains enough water to act as a lubricant.

Ground pressures of wheeled vehicles vary directly with load and tire pressure. A rule of thumb that takes into consideration both of these factors is that actual contact pressure in pounds per square inch is equal to the inflation pressure plus the number of plies of the tire.[2] This rule can be applied to the following ranges of inflation pressures and ply ratings to estimate ground pressures for the following types of vehicles *(83)*.

	Inflation pressure (pounds)	*Ply ratings (numbers)*
Agricultural tractors (rear wheel)	12–32	2–8
Passenger cars	18–30	4–6
Light trucks	30–55	6–10
Trucks and busses	40–80	6–18
Mining and logging trucks	35–80	10–32

The size of tire and diameter of the wheel also affect ground pressure. For equal loads, inflation pressures, and widths, the tire having the largest diameter will have the largest contact area and hence less area pressure. For tires having the same contact area, the narrow tire with a large diameter will not sink so deep as the wide tire with a small diameter; also, narrow tires tend to slip less *(6)*. The advantages of large wheel diameter are opposed, however, by higher torques, heavier gears, heavier and costlier tires, and occasionally by a higher center of gravity *(75)*. High ribs on tractor tires tend to increase ground pressures by reducing contact areas; mean area pressures beneath the ribs have been found to be 4 to 5 times greater than pressures of ribless tires *(76)*.

Not only must the weight of crawler tractors be considered, but also the ground pressure of logs snaked behind them. A 16-foot log, for instance, with a middle diameter of 14 inches and a density of 60 pounds per cubic foot, weighs about 1,200 pounds. Simply calculated, if this weight were distributed over a bearing width of 3 inches along the log length, ground pressure would be 2.1 pounds per square inch.

Area Disturbed

A primary factor that affects the degree of soil compaction from logging is the extent of areal disturbance, which here is considered roughly equivalent to the area of soil compaction. Also, a certain amount of soil loosening may be associated with soil compaction, as when furrows are plowed in the soil by skidded logs. Denudation of cover also results. Thus, runoff and erosion from logged areas cannot be charged solely to compaction. Probably, however, soil compaction over a logged area is more universal than either soil loosening or soil denudation.

Information from the Pacific Northwest and California reveals some consistency in the percentage of area that would probably be compacted during a logging operation. Generally, skidroads take up about 20 percent of an area, but the total area compacted—considering loading sites and trails over which logs are moved to the skidroad—may run as high as 40 percent. Surveys of several cutting areas in Washington and Oregon have shown that 10 percent or more of the ground is completely denuded of vegetation during the timber harvest *(27)*.

In the pine-fir forest of California, Fowells and Schubert *(20)* found 22 percent of a tractor-logged area bare of vegetation. In northeastern California, Hormay *(31)* found that 14 percent of the area had been subjected to skidding and was

[2] Personal communication from Sterling J. Knight, Chief, Army Mobility Research Center, Waterways Experiment Station, Vicksburg, Miss. May 1956.

relatively free of vegetation; 24 percent was covered by slash. Steinbrenner and Gessel *(79)* reported that tractor skidroads took up an average of 26 percent of the area of nine typical logged areas in the Douglas-fir region. In the ponderosa pine type, Garrison and Rummel *(25)* found on an average that during logging operations 22 percent of the ground was denuded of cover.

In a logging operation in old-growth Douglas-fir and hemlock in western Washington, Rapraeger *(66)* found that truck and tractor roads averaged one road every 3⅓ chains (perhaps 5 to 10 percent of the area); ground cover was changed on 44 percent of the area by the addition of slash or by crushing of the brush by tractors and logs.

According to Steinbrenner,[3] the human element is important in determining the area of tractor-logged old-growth Douglas-fir that goes into skidroads: some tractor operators like to build roads and create far more skidroads than are necessary.

From aerial photographs, Olson *(56)* determined that bulldozed spurs and truck hauls crossed a square mile of typical jammer operation in northern Idaho at least ten times. This amounted to about 5 percent of the area or double that if right-of-way clearing is included.

In the one study on logging disturbance in the East, 31 percent of one area was reported as disturbed: 14 percent was disturbed by felling, 9 percent by bunching, and 8 percent by skidding. The logging was performed during a stand-improvement cutting in upland hardwoods in southern Illinois in which material was removed in log-lengths. In a lighter cut in which about one-half as much volume was removed in tree lengths, 18 percent of the area was disturbed: 8 percent in felling, 8 percent in bunching, and 2 percent in skidding *(29)*.

Garrison and Rummell *(26)* observed that the area and degree of disturbance depended on the type of logging—tractor, cable, or horse. They classified two kinds of disturbance: (1) Deep soil disturbance, where soil was displaced or torn up to a depth of 1 inch or more—and sometimes to a depth of a few feet; and (2) shallow soil disturbance, where the ground cover was absent and soil was disturbed to a depth of less than 1 inch. Percentages of logging areas so classified were as follows:

	Tractor	*Cable*	*Horse*
Deep soil disturbance	15.0	1.9	2.3
Shallow soil disturbance	5.9	13.3	9.5

Tractors caused the most serious disturbance: most of it came from ground-skidding the logs and constructing spur roads and landings. When arch-logging was practiced, the depth to which a given soil was disturbed was less. Roughly, horse and cable logging caused about one-seventh the deep soil disturbance caused by tractor logging, and about twice the shallow soil disturbance.

Additional pressures on the soil may be exerted in using tractors with dozer blades for pushing dirt, boulders, and stumps. Appearance of the compacted soil often indicates horizontal slippage in addition to vertical compression, with hard bricklike cakes of soil formed to a depth of 4 inches between the cleats on tractor treads.[4]

Fobes *(16)* reported little soil disturbance from Wyssen cable logging in upper New York State and Canada. Skid trails were scattered and discontinuous so that water was not concentrated in any one place. More soil was exposed in trails made by men walking up and down the main line than by skidding.

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[3] Personal communication from E. C. Steinbrenner, Forest soils specialist, Weyerhauser Timber Co. Forestry Research Center, Centralia, Wash. August 1957.

[4] Personal communication from William C. Bullard and Melvin H. Burke, Pacific Northwest Region, U. S. Forest Service, Portland, Oreg. July 1957.

An inspection on the Wyssen logging tryout on the Okanogan National Forest indicated removal of herbs and litter on less than 5 percent of the area of operation, no deep soil disturbance, and no evidence of compaction on a sandy volcanic ash soil.[5]

The degree-of-disturbance/type-of-equipment relationship is governed somewhat by topography. Ruth and Silen *(70)* have recommended that, to prevent undue soil disturbance and watershed damage, tractor yarding should be limited to slopes not exceeding 25 to 35 percent; high-lead yarding should be used on steeper slopes. Sampson and Shultz *(71)* have reported that crawler tractors are ineffective in clearing brush from slopes of 50 percent or more.

The extent of areal disturbance may be related to soil type also. In south-central Oregon, 28 percent of an area of coarse pumice soil (loamy sand) was denuded of vegetation by tractor logging as compared with 18 percent of an area of finer-textured soil *(26)*.

Frequency of Travel

Generally the greater the number of passes over an area, the greater the compaction up to a point of maximum density. At the first pass the contact area depends on the deformation of the soil: the deeper the rut, the greater the area over which the pressure is exerted, and the less the pressure per unit area. At the second pass, the wheels roll in the track made during the first pass, so the contact area is smaller and the pressure in the contact area is higher *(76)*.

Weaver *(91)* found that when a tractor tire was passed 10 to 20 times over the same track in a loam soil, the soil was compacted to a depth of 9 inches; two passes compacted the soil to a depth of 6-inches. Free, Lamb, and Carleton *(22)* found that the upper 2 inches of a silt loam increased in bulk density from 1.32 to 1.50 after one trip with an empty farm truck or tractor (an estimated reduction in total pore space from 50 to 43 percent). Four trips with an empty truck increased bulk density from 1.24 to 1.58 percent (53 to 40 percent pore space). Weaver and Jamison *(92)* observed that the greatest increase in bulk density occurred during the first four of ten passes by a tractor tire.

Steinbrenner *(78)* found that four trips with an HD–20 tractor (weight about 20 tons) reduced macroscopic pore space from 26 to 17 percent in the upper 3 inches of soil and the infiltration rate from 80 to 10 cubic centimeters per minute when the soil was dry; when wet, one trip had the same effect. Results of this study (fig. 1) illustrate the common finding that infiltration rate is the soil characteristic most sensitive to compaction. This study was conducted in an area of undisturbed old-growth timber and fine-textured soils.

Garrison and Rummell *(26)* have pointed out that topography affects frequency of use and thus also affects soil disturbance. Deep soil disturbance was 2.8 times greater on slopes of 40 percent than on lesser slopes. This was due in part to fewer possible logging roads and consequently heavier use of available roads. In another report, these authors reported skid trails 2 to 4 feet deep in long and heavily used trails *(25)*. Implications are that the degree of disturbance would increase directly with steepness of slope until the slopes become so steep as to be inaccessible and thus saved from compaction. Crawler tractors can operate on slopes up to 50 or 55 percent but cannot maintain maximum mobility on slopes of more than 30 percent *(17)*.

Soil Factors

The effect of logging on the physical characteristics of soils will depend in part on their ability at any one time to support loads. This supporting capacity—or

[5] See footnote 4, p. 5.

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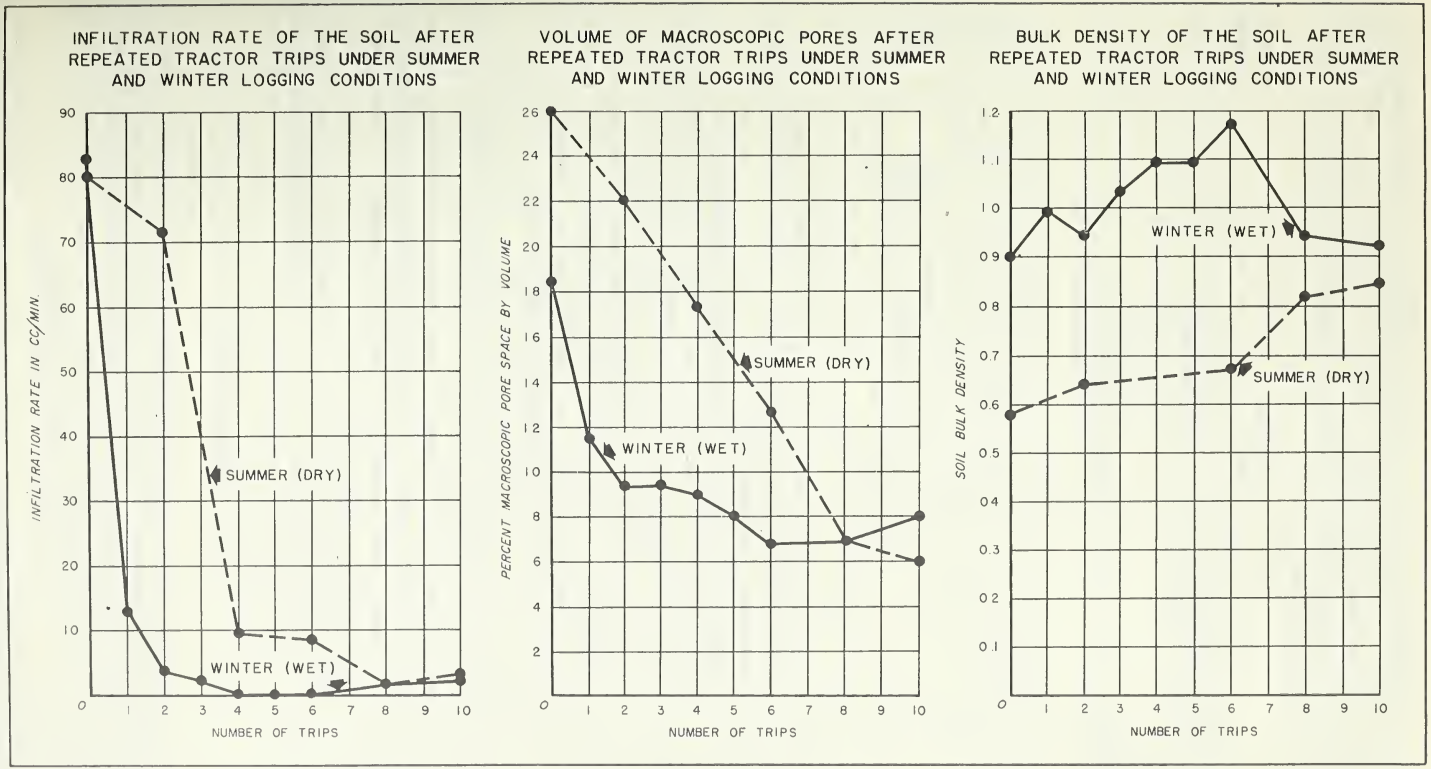

FIGURE 1.—Effect of repeated tractor trips on infiltration, macroscopic pores, and bulk density (78).

resistance to deformation—will vary largely according to soil texture, porosity, and moisture content. For soils of any one texture and density, the supporting capacity will fluctuate with the moisture content. A rough concept of supporting capacity can be gathered from the following tabulation prepared by the Food and Agriculture Organization *(17)*:

	Pounds per square inch		*Pounds per square inch*
Marshland and peaty soils	2.8	Limestone	14–57
Alluvial tracts on loose soil	7.1	Soft clay	14
Dry sand	28	Semidry clay	28
Wet sand	57	Dry clay	57
Fine gravel	71	Solid rock	356
Coarse gravel	28–85	Broken rock	71
Packed gravel	114	Packed snow	128

Though their values may be overly precise estimates of a very gross characteristic, they do indicate that, in terms of ground pressures of logging equipment, many areas have soils that can support the heaviest vehicles. However, the surface of soils that can easily support heavy loads may be so compacted that their macroporosity and rates of water movement are markedly reduced. Thus the idea that compaction is not a problem in stony soils may be erroneous. According to Bullard and Burke, many forest soils in the Pacific Northwest are quite stony, yet become severely compacted by tractors. Only the very stony glacial drift does not compact.[6]

Under wet conditions, silt loams have the lowest supporting capacity; they tend to remold and lose strength under continued use.[7] Clays and sandy loams have much greater capacities to support traffic.

The more porous the soil initially, the greater the compaction depth. For instance, in wet Cecil clay, tractor-tire compaction ranged from 17 inches below the surface in the loosely compacted state to 12 inches in a heavily compacted state *(35)*.

Up to certain limits of moisture content, the wetter the soil the greater the opportunity for compaction. As has been noted, Steinbrenner *(78)* in the Pacific Northwest found an 80-percent reduction in infiltration and a 50-percent reduction in macroscopic pore space after four passes on a dry soil with an HD–20 tractor; but when the soil was wet, one trip had the same effect. When subjected to excessive use, Ramona loam in a dry condition was compacted to a depth of 9 inches and when wet to a depth of 24 inches *(59)*.

Doneen and Henderson *(12)* found a linear inverse relationship between infiltration rate of a sandy loam and its moisture content, at the time of tractor passage, over a range from permanent wilting percentage to a moisture level slightly above the moisture equivalent.

In Cecil clay and Davidson loam, Weaver and Jamison *(92)* found that peak compaction from tractor treatments occurred at moisture contents near the lower plastic limits and at optimum plowing moistures.

Effect on Soil

Since the amount soils are compacted depends on their texture, porosity, moisture content, and of course on the compactive force exerted, one can expect a wide range of results from studies reporting the depth to which compaction occurs and its effect on such physical characteristics of the soil as bulk density and pore space. Nevertheless, certain broad effects on soil do stand out.

[6] See footnote 4, p. 5.

[7] Waterways Experiment Station, U. S. Army Corps of Engineers. Trafficability of soils—soils classification. TM 3–240, 11th Supplement. 1954.

For instance, most studies show that the depth to which compaction occurs does not exceed 12 inches directly below the bearing surface and that laterally the effect does not extend farther than 12 to 18 inches. Reed *(68)* found that crawler tractors compacted the soil to a depth of 12 inches while both steel and rubber tires compacted the soil to an 8- to 10-inch depth. All types compacted the soil as much as 12 to 15 inches to either side of the center line.

In studying the effects of a wheeled tractor on loam soil, Weaver *(91)* found that the maximum bulk density beneath the track center line decreased laterally to a maximum of 18 inches. Under maximum loads the soil was compacted to a depth of 9 inches; no compaction was found at the 3-inch depth—instead, the soil was loosened.

Some idea of the effect that tractors of different weights have on macropore space in the upper 2 inches of soil is evident from figures given by Swanson *(81)*:

Tractor weight (pounds)	*Crop*	*Fertilizer (pounds per acre)*	*Reduction in macropore space between traveled and nontraveled area (percent)*
4,020	Corn	1200	27
2,880	Carrots	1200	22
4,020	Corn	600 (+20 tons manure)	30
2,880	Carrots	600 (+20 tons manure)	8

Soil samples were taken from areas over which the rear tractor wheel had passed six times during cultivation. Apparently the manure had a cushioning effect under the lightweight tractor, but this effect broke down under the heavier tractor.

In the Douglas-fir region, the effects of logging on physical characteristics of silty clay and clay loams were reported by Steinbrenner and Gessel *(79)*. Soils from nine tractor-logged areas had a 35-percent loss in permeability, a 2.4 percent increase in bulk density, and an 11-percent decrease in macropore space as compared with soils in undisturbed timber. Tractor roads showed a 92-percent loss in permeability, a 35-percent increase in bulk density, and a 53-percent loss in macropore space.

Effect on Infiltration

The few measurements that have been made indicate that soil compaction by vehicles strongly reduces infiltration. Doneen and Henderson *(12)* reported that the infiltration rate of a sandy loam was markedly reduced by two or more passes of a heavy tractor soon after irrigation. Rates were 1.4, 0.6, 0.3, and 0.2 inches per hour for 0, 2, 6, and 12 passes, respectively. Tests made at successively longer periods after irrigation indicated that little could be gained by delaying tillage operations more than 7 days even though after 19 days there was still a significant difference in rates.

According to Parker and Jenny *(59)*, a stream of water traveled three times farther in an irrigated furrow in dry loam compacted by excessive tractor use than in an uncompacted area; after compacting under wet conditions the stream of water traveled 15 times farther.

Trimble and Weitzman *(86)* 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 the B-horizon.

Compaction by Trampling

A search of the literature revealed very little information on ground pressures exerted by livestock. Blair (5) cited calculations by Ballu to show that an ordi-

nary farm horse exerts pressure of 2,000 to 4,000 grams per square centimeter (29 to 57 pounds per square inch) if the ground is hard enough for the whole weight to be taken by the shoes. According to a recent FAO bulletin (*17*), a horse exerts a pressure of 1.4 kilograms per square centimeter—equivalent to 24 pounds per square inch.

To get additional data, ground pressures exerted by sheep and cattle were calculated by the author, who measured the area of hoof prints and related it to weight. Results were as follows:

	Average bearing area (square inches)	*Average weight (pounds)*	*Ground pressure (pounds per square inch)*
Sheep	13.0	120	9.2
Cattle	56.4	1,350	23.9

These pressures are for static loads only. During movement, pressures would be greater as body weight is distributed over smaller bearing surfaces; since animals often put their entire weight on one foot, pressures may exceed the above by four times.

Effect on Soil

The effect of grazing has been shown in several studies by comparing bulk density of grazed and ungrazed soils. Alderfer and Robinson (*2*) found that compaction from grazing was limited mostly to the 1-inch surface layer. On a variety of pasture sites on clay loams and sandy loams in Pennsylvania, bulk densities in this layer ranged from 1.54 to 1.91 for heavily grazed sites and from 1.09 to 1.51 for ungrazed and lightly grazed sites. Noncapillary porosity for the two conditions ranged from 3 to 10 percent and 15 to 33 percent, respectively. In a later paper the authors reported a platy structure in the 1- to 5-inch depth that evidently did not affect bulk density but would probably affect infiltration capacity and runoff (*69*).

In second-growth hardwood stands in central New York, Chandler (*8*) found that bulk density of heavily grazed areas was 1.15, ungrazed areas 0.92—a statistically significant difference. The depth to which the samples were taken was not given; the soils were principally loams or silt loams. The increase in volume weight was attributed to three factors: The trampling effect of cattle, a lower organic-matter content, and a lower percentage of large aggregates.

In the Allegheny River watershed, Trimble, Hale, and Potter (*85*) found average bulk densities of 0.92 to 0.51 in the A_1 horizon of grazed and ungrazed woodlands, respectively, and densities of 1.07 and 1.01 in the lower A horizon. Associated noncapillary porosities were 12.6 percent and 23.4 percent of the A_1 and 13.7 percent and 14.8 percent in the lower A horizon. Most of the grazed woodlands studied were judged to be in a moderate grazing-damage condition.

In Ohio, Auten (*3*) found that the average weight of 180 samples of air-dried soil, of equal volume taken to a depth of 9.25 inches, was 834 grams for ungrazed woodland and 969 grams for excessively grazed woodland. The grazed soil was 15 percent heavier.

In a study of woodland grazing in western North Carolina (*36*), the extent of soil compaction, as measured by the difference in total porosity of grazed and ungrazed samples, was found to vary with use by forest type. In the most heavily grazed type, cove-hardwood, total porosity in the 2-inch depth was reduced 42 percent; in the more lightly grazed oak-hickory type, 15 percent; and in the pine-oak ridge type (which possessed little forage), 6 percent. Comparable values for the 2- to 4-inch depth were 56, 12, and 4 percent. These changes occurred over an 8-year period during which cattle were on the area only during the summer months.

Total porosity and noncapillary porosity were found to be greater in ungrazed than grazed woodlands in southern Wisconsin (77). For six paired areas, total pore space ranged from 64.5 to 72.5 percent in ungrazed areas as compared with 57.5 to 67.0 percent for grazed soils. Associated ranges of macroscopic pore space were 16.5 to 37.0 percent and 12.5 to 18.0 percent.

Bulk density of a heavily grazed silty clay loam in three South Dakota shelterbelts averaged 1.22 as against 1.01 for comparable areas under protection. Total porosities, respectively, were 51.7 and 57.3 percent, the difference being largely the difference in large pore space, 7.6 as against 14.1 percent (67).

Little is known about the soil depths compacted by trampling. As noted, Alderfer and Robinson (2) found that cattle trampling was limited mostly to the 1-inch surface layer. In the 1- to 3- and 3- to 6-inch layers, bulk density was not affected by intensity of grazing. In a more extensive second paper describing conditions in 32 permanent pastures in Pennsylvania (69), the authors found that the 1-inch depth with high organic-matter content was not compacted, whereas the 1- to 5-inch layer was compacted and had a platy structure. Keen and Cashen (38) found that sheep compacted light sandy soil to a depth of 10 cm.; the greatest compaction occurred at the 3- to 4-centimeter depth. Their results were obtained by measuring the resistance that the soil offered to the passage of a rod forced through it.

Big-game animals (deer and elk) in the Pacific Northwest often cause serious trampling compaction on saturated soils along the receding snowline in spring. Hoofprints 4 inches deep and sometimes to bedrock in shallow, wet soils have been observed. When the soil dries out later, it may become hard and support only a scant cover.[8]

Effect on Infiltration and Percolation

Soil compaction from trampling has a major effect on soil moisture movement. For instance, in the woodland-grazing study in North Carolina cited above, infiltration was reduced 91 percent in the cove-hardwood type and 67 percent in the oak-hickory type by grazing. At the 2- to 4-inch depth, percolation in each type was reduced 91 and 32 percent (36).

Alderfer and Merkle in a study in Pennsylvania reported that the percolation rate of Hagerstown silty loam at a forest site was 25 cubic centimeters per minute as compared with 18 in unpastured bluegrass soil and 5.5 in bluegrass permanent pasture (1). Their measurements indicated that heavily pastured soil may become nearly as impervious as land used for intertilled crops.

The effect of trampling on runoff and erosion on granitic soils in Idaho was reported by Packer (58) from a study in which trampling was simulated by compacting the soil surface with a steel bar. Runoff and erosion were found to vary with the amount of ground cover disturbance. In wheatgrass or cheatgrass with a density of 90 to 95 percent, trampling had no significant effect even when 100 percent of the area was affected. With a cover of 80 to 95 percent, disturbance of 40 and 60 percent of the area increased runoff and erosion past previously established safe limits.

Peele (61) noted that heavy grazing on wet clay loam so compacts the surface that low infiltration results even under a good sod: the infiltration rate for the grazed wet soil was 0.40 inch per hour after 1 hour of simulated rainfall, whereas for ungrazed wet soil it was 2.12 inches after 2 hours of testing. Differences in results between this study and Packer's (58) may be due to differences in soil textures.

In the Wisconsin study previously noted (77), permeability of 2-inch soil cores

[8] See footnote 4, p. 5.

from ungrazed woods was 3 to 245 times greater than that of the grazed soils. On soil cores taken from the A_1 horizon of grazed pastures in the Allegheny watershed, Trimble, Hale, and Potter (*85*) found an average percolation rate of 30.2 inches per hour; on ungrazed soil 132.0 inches per hour. For the lower part of the A horizon the difference was much less, the rates being 13.1 and 17.0 inches per hour for the two conditions.

Trampling by Man

Though compaction of the soil from a man walking on it might be considered a minor disturbance, the ground pressures produced are considerable.

Blair (*5*) made the interesting (but erroneous) observation that, with a contact area of 35 square centimeters, a man weighing 150 pounds would exert a pressure of about 200 grams per square centimeter. An FAO bulletin (*17*) states that the weight of a man on one foot exerts a pressure of about 300 grams per square centimeter—also, perhaps, an erroneous value. The correct pressure for Blair's data is 1,940 grams per square centimeter or 27.6 pounds per square inch. Since the contact area was obtained by measuring the scuffed area of one boot, the standing-on-two-feet pressure would be 13.8 pounds per square inch.

A few measurements of bearing area were taken by the author which, when related to the individual's weight, gave the values shown below:

	Area of bearing surface (square inches)	*Weight (pounds)*	*Ground pressure (pounds per square inch)*
Men	22.6	135	6.0
	24.0	150	6.2
	25.2	165	6.5
Women	12.3	102	8.3
	6.9	108	15.7
	10.7	128	12.0
	12.1	160	13.2

Bearing surfaces of shoe soles were determined by measuring the area of imprint made on a piece of carbon paper. Variations in pressure exerted by women are due in part to differences in shoe styles. Like the ground pressures given for livestock, these values represent static loads only.

Recreational use of forests by large numbers of people can change the physical properties of the soil. In two public forest parks in Connecticut, Lutz (*49*) found greater bulk densities and less pore space in picnic areas than in unused areas. Average values are given below.

	Bulk density		*Pure volume percent*	
	0–10 cm. deep	*10–20 cm. deep*	*0–10 cm. deep*	*10–20 cm. deep*
Merrimac sand:				
Used	1.37	1.46	48	45
Unused	1.01	1.28	60	51
Cheshire sandy loam:				
Used	1.30	. . .	50	. .
Unused	1.06	. . .	59	. .
Holyoke sandy loam:				
Used	1.06	1.13	59	56
Unused	0.91	1.07	65	59

Infiltration in the trampled area was found to be only a fraction of that on unused areas. An average of 20 minutes was required for a liter of water to enter tram-

pled sand; on the unused area only 3 minutes were necessary. Comparable values for a sandy loam were 86 and 4 minutes.

In his review of previous investigations, Lutz cited a study in Switzerland, which reported that trampled forest soil showed less than half the air capacity of undisturbed forest soil and had an infiltration rate of only one-fifth to one-sixth as great. According to Meinecke (*53*) excessive tourist travel in the California redwood parks has compacted normally loose and elastic soil:

> In time such soils become firm and dense and finally form a hard and tough surface sheet which is more or less impermeable to air, sheds water readily and impedes the normal exchange between soil and atmosphere. The soil below the sheet becomes abnormal and offers unfavorable living conditions to the roots . . . Foot paths and roads often remain completely barren for many years after travel over them has ceased.

Compaction by Rainfall Impact

Rainfall causes compaction when its striking force is absorbed by bare soil; a cover of vegetation and litter effectively neutralizes this force. Removing the cover subjects the soil to forces of considerable magnitude: according to Nichols and Gray (*55*) a 2-inch rain falling at a velocity of 20 miles per hour possesses 6,000,000 foot-pounds of kinetic energy per acre or 138 foot-pounds per square foot. Energies involved in rainfall impact over a range of rainfall intensities are given in table 1. The first three columns of data are from Kittredge (*39*). In calculating raindrop volume (to estimate number of drops), the shape of the drops was considered as spherical. For heavy rainfalls and greater downpours the force exerted ranges from about 0.15 to 2 foot-pounds per square inch.

Ground vegetation and litter covering the soil absorb most of this energy. A small portion is absorbed by interception and retention of some of the rainfall in the tree canopy. Tree canopy would have a larger effect except that much of the intercepted rainfall drips off and raindrops 2.0 millimeters in diameter can attain 95 percent of their terminal velocity in a fall of 16 feet, and 3.0- to 6.0-millimeter drops in a fall of 25 feet (*44*).

Table 1.—*Kinetic energy and number of drops for rainfall of various intensities*

	Intensity	Median diameter	Velocity of fall	Drops per square foot	Kinetic energy
	In. per hr.	*Mm.*	*Ft. per sec.*	*No. per sec.*	*Ft.-lbs. per sq. ft. per hr.*
Fog	0.005	0.01	0.01	6,264,000	4.043×10^{-8}
Mist	.002	.1	.7	2,510	7.937×10^{-5}
Drizzle	.01	.96	13.5	14	.148
Light rain	.04	1.24	15.7	26	.797
Moderate rain	.15	1.60	18.7	46	4.241
Heavy rain	.60	2.05	22.0	46	23.47
Excessive rain	1.60	2.40	24.0	76	74.48
Cloudburst	4.00	2.85	25.9	113	216.9
Do	4.00	4.00	29.2	41	275.8
Do	4.00	6.00	30.5	12	300.7

Trimble and Weitzman (*87*) found little difference between rainfall intensities measured in the open and under a 50-year-old mixed hardwood stand. They concluded that a high tree canopy has only limited value in reducing erosion potential of rainfall before it reaches the forest floor; the major role of the forest is to furnish a soil-protective layer of litter and humus. However, a heavy stand of reproduction or a forest with a canopy that reaches close to the ground might be expected to reduce ground rainfall intensity.

According to a rainfall impact-soil splash study by Osborn (57), 95-percent control of raindrop energy requires about 2,000 pounds per acre of short sod grasses, or 3,500 pounds of ordinary crops or grasses, or 6,000 pounds of tall coarse crops and weeds.

Lunt (*48*) found that removal of litter under red pine resulted in compaction of a gravelly fine sandy loam in as short a period as 2½ years. He ascribed this compaction to rainfall impact: "Absence of protective litter allows the rain to compact the soil to the extent that a crust forms on the surface." The major effect was in the 1-inch surface layer. Average bulk densities at this depth for plots with and without litter were 0.865 and 0.991, respectively; at the 1- to 2-inch depth 0.991 and 0.998. In terms of total porosities these are equivalent to 67 and 63 percent for the upper inch and 63 and 62 percent for the second inch.

As has been noted previously, an important effect of compaction is to reduce the macropore space in the soil. Baver (*4*) cites a study of Wollny which showed that total porosity of three different soils without cover averaged 56 percent as compared with 59 percent for similar soils protected by a cover crop. Macropore space was particularly affected, being reduced by about one-third from 39 to 28 percent. Since these are the pores that provide passage for the great bulk of water through the soil, this reduction has considerable effect on water transmission.

Reduction in total porosity may also be caused partially by deposition of fine particles from turbid surface runoff, in the macropore space. This process was first described by Lowdermilk (*47*). The combined effects of rainfall impact and soil sealing have been portrayed in a fine series of photographs by Duley (*13*), which show formation of dense surface layers. Dutta (*14*) has pointed out that the filling of shrinkage cracks in bare soil by the silt from surface runoff causes them to gradually disappear, the loss of expansion opportunity resulting in a permanent reduction of porosity.

Since rainfall impact and surface runoff are effective in increasing soil density only on bare soil, any compaction they produce is in addition to that which occurs during the removal of the vegetal cover. Their most important effect may be the continuation of compaction after disturbance has ceased.

The Compaction Process

The soil compaction process involves a stress or external force applied to the soil; resistance of the soil to the stress; and soil compression (reduction in soil volume) and settlement of the load as the resistance is partially overcome. This process has been described recently by C. Y. Li (*45*) as follows:

> If applied stresses exceed the shearing strength or resistance of the soil, local failure begins and the load starts to sink into the soil. As the load sinks, the soil under the load is pushed downward and outward. This motion will mobilize more and more resistance, consisting not only of the increased resistance due to lateral confinement from depth but also that due to the increase in soil density that results from the settlement motion itself, provided the soil is not completely saturated. The settlement stops when equilibrium between stresses and resistance is reached.
>
> If the resistance of the soil is relatively high compared with the stresses, the load will cause very little settlement. . . If the resistance is extremely low in comparison with the stresses, the load will cause a complete sheer failure of the underlying soil by sinking deep and fast and replacing the volume of soil by pushing it in an outward direction. This completely disturbed state may result in compaction of the soil under the load and loosen the soil on the sides. The total net reduction in voids is questionable—energy is spent in compacting one portion of the soil and, at the same time, loosening another portion. Both

compacting and loosening involve movement of particles and require energy to overcome the frictional resistance.

When the soil is compacted, particles are brought closer together and fine grains are forced into the voids between coarse grains, thus increasing soil density. Buchanan (7) suggests that in addition to the rearrangement of the grains there is an interlocking of particles under stress. At low moisture contents the water films on the particles bind them together so as to form arches in the soil, which are capable of bearing weights greater than those that could be supported by individual particles without deformation.

Soil aggregates react differently to stress than do individual particles. Blair (*4*) found that a gradually increasing stress on soils in good tilth gives a stress-compression curve with a stepladder effect. This could be due to the sudden collapse of aggregates in the soil and would appear to indicate a soil of good structure.

Day and Holmgren (*10*) have shown that, under stress, volume changes of 1- to 2-millimeter aggregates from Aiken clay loam and Yolo silty clay loam were mainly due to plastic deformation. At the lower plastic limit (the moisture content at which the soil barely adheres together when rolled out into ⅛-inch diameter threads, or the moisture content at which a soil begins to take on plastic properties) for the Yolo soil of 25 percent, bulk density increased from 0.78 to 1.23 under a pressure of 7 pounds per square inch and interaggregate spaces comprised an appreciable portion of the total volume; under a pressure of 21 pounds the bulk density rose to 1.69 and interaggregate spaces almost completely disappeared. At 15 percent moisture content, a pressure of 21 pounds per square inch gave a bulk density of 1.07. The Aiken clay loam proved to be much more resistant: at moisture contents slightly above the lower plastic limits, bulk densities were 0.62 to 1.05 at 7 pounds pressure and 0.60 to 1.14 at 21 pounds. Flattening of the aggregates against each other caused a more uniform distribution of the load and thus served as a restraining influence against unlimited deformation.

As noted earlier, the depth to which compaction extends varies according to the force involved and the moisture content of the soil. Theoretically, if the soil is considered as a perfectly homogeneous and elastic material without pores, pressures directly beneath the load are inversely proportional to the square of the depth. As given by Krynine (*41*):

$$\text{Vertical pressure} = \frac{kP}{Z^2}$$

where P = load, Z = depth at which pressure is desired, and K for the pressure directly beneath the load = 0.48. For vertical pressure away from the center, lesser values of k are used depending on depth and lateral displacement. Krynine suggests that the use of this equation is not advisable close to the loaded surface, and at shallow depths better results may be expected for clays than for sands. Under field conditions, as noted earlier, compaction does not always decrease with depth; Weaver (*91*) observes that, under maximum compaction from tractors, the upper 3 inches of the soil was loosened.

Little information could be found on the time required for a load to compress the soil. A few measurements made on a fine sandy loam by the author indicated that for this soil and for the stresses applied, most of the compression takes place within the first 30 seconds. Figure 2,*A* illustrates the time relation for two different bulk densities. Compression values were obtained by adding successive equal stress increments of 0.5 pound per square inch and recording the compression at time intervals shown. In engineer jargon "compaction" results from instantaneous loading, whereas "consolidation" refers to the state of the soil after a load application for sufficient time for the soil to become fully adjusted.

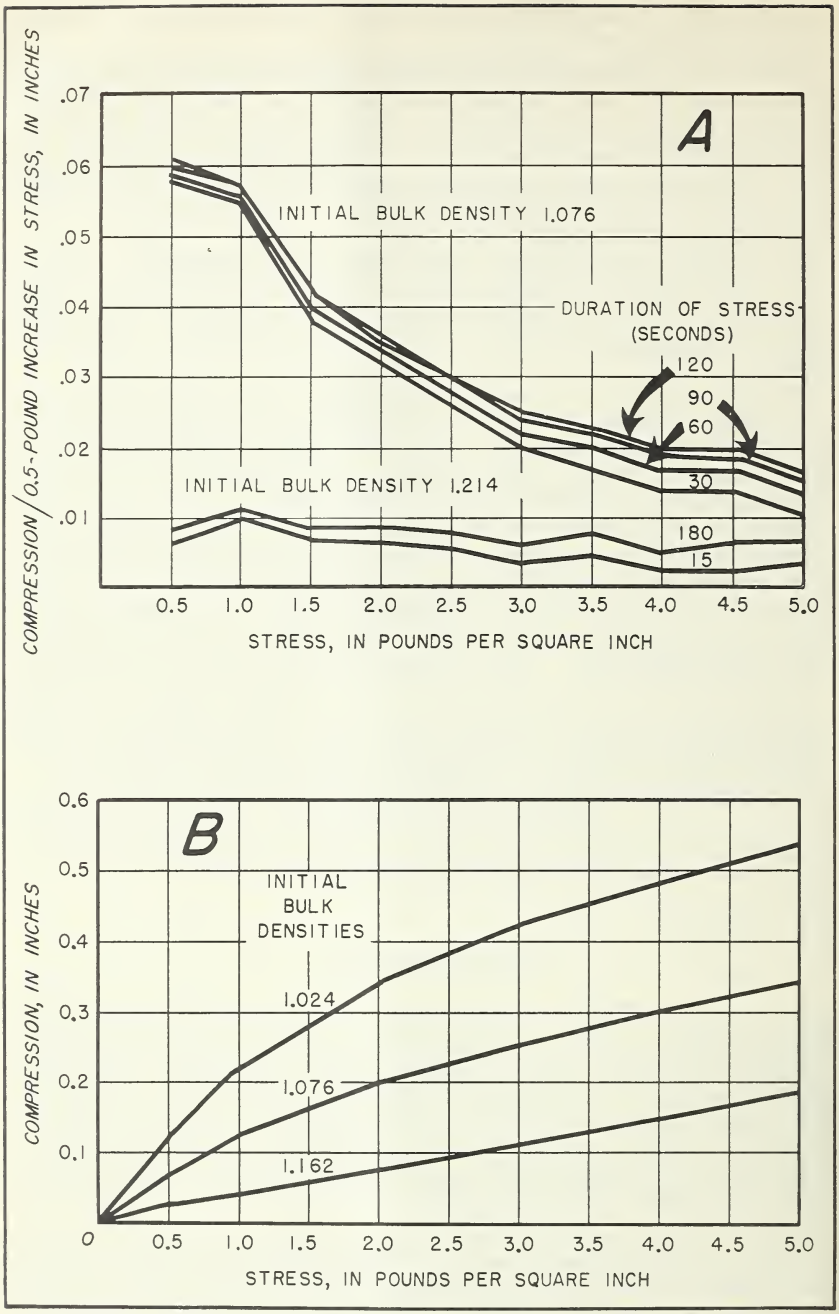

FIGURE 2.—Effect on soil compression of: *A*, Time application of load, and *B*, initial bulk density.

Site Factors That Affect Compaction

Soil texture and structure, soil density, moisture content, organic content, and soil frost are site factors that affect the rate and degree of soil compaction. Generally, the coarser the soil, the lower its density, the greater its moisture content, and the lower its organic content, the more liable it is to compaction. Soil frost, under different conditions, can either facilitate or hinder compaction.

Soil Texture and Structure

According to an analysis by Krynine (*42*), maximum densities (obtained by several methods of laboratory and field compaction) decrease systematically in the order of decreasing grain size from gravel to clay. For sands and gravels, maximum densities were obtained by using heavy smooth-wheel rollers, whereas for clay they were obtained by using tamping (sheepsfoot) rollers. Apparently wheel rollers produced vibration and wavy action to which sands and gravels are sensitive. Clays, on the other hand, require a consolidating action and readjustment of flat particles, which is best accomplished by a tamping action.

Hardpans produced by compaction from vehicles or trampling are most commonly found in medium textured soils—loams, sandy loams, and silt loams (*65*). This is in accordance with Huberty's finding that soils with a wide range in particle size compact to much greater densities than soils of uniform grain size (*32*). For instance, spherical particles of the same diameter with tetrahedral packing will have 74 percent solids and 26 percent pore space. By adding particles of much smaller diameter, the solid volume can be increased to 93 percent of the total (*50*).

Soil structure also affects the degree to which a soil can be compacted. Well-aggregated soils have low bulk densities and are highly permeable. Under compactive forces, the aggregates are crushed, particles fill the interaggregate spaces, and permeability is reduced. Trampling, for instance, destroys the aggregates normally associated with grass cover. In Pennsylvania, Alderfer and Merkle have observed that land in bluegrass or other sod-producing grasses, if not subjected to compaction, may develop a degree of granulation equal to or better than that found in forested land (*1*).

Soil Density

Under equal stress, compression will be a function of the initial density, all other elements being the same. The less the density, the greater the compression. This is illustrated in figure 2,*B*, which shows stress-compression for three densities of a fine sandy loam. These data were obtained by adding successive increments of 5-pound loads to a bearing surface 6 inches in diameter; each increment amounted to 0.5 pound per square inch. In its most porous condition, relatively small changes in bulk density appear to yield relatively large compressions. Thus a 5-percent increase in bulk density from 1.024 to 1.076 reduced compression from 0.540 to 0.342 inch or 37 percent. A 13-percent increase in bulk density from 1.024 to 1.062 reduced compression 65 percent. Within the range of these data the tendency towards a straight-line stress-compression relationship as bulk densities increase is also evident. Whereas in the less dense soils compression per unit increase of weight markedly decreased, a fairly uniform rate was found for the most dense soil.

Markwick (*52*) has shown that an increase in the compacting force has a greater effect upon clay than upon sandy and silty clay. Clay with a density of 95 pounds per cubic foot, under ordinary compaction, increased 22 pounds per cubic foot in density when it was subjected to heavy compaction. A similar treatment on

sandy and silty clay with a density of 115 pounds per cubic foot increased the density by 10 pounds.

As noted before, increases in bulk density of the soil due to compaction are not as good evidence of compaction as certain other soil properties. Fountaine and Payne (*19*) have noted that one rolling with even an abnormally heavy tractor seldom reduced bulk density as much as 10 percent. Often, however, when only negligible changes in density occurred, the soil appeared to be seriously puddled, indicating that changes in air or water permeability might be of greater magnitude. It is interesting that Merz and Finn (*54*) have reported that bulk density differences due to compaction were not significantly different at the 5-percent level whereas associated differences in infiltration were significantly different at the 1-percent level. Difficulties in detecting bulk density differences may be ascribed to the difficulties in measuring the bulk density of the layers most greatly affected. These layers may be thin and difficult to sample in the undisturbed state.

Soil Moisture Content

Considerable study has been given to the relationship between soil moisture and compaction, in respect to the engineering objective of determining the moisture content that would give the greatest degree of compaction under equal amounts of stress. These studies have shown that the greatest compaction can be achieved for the least expense when the soil is at a moisture content slightly less than the plastic limit (*52*).

It follows that this is the moisture content at which soils can be most compacted by logging or trampling. For data given in a report of the U. S. Forest Service and the Waterways Experiment Station, Corps of Engineers, this moisture content was about midway between soil moisture tensions of 0.06 and 15 atmospheres corresponding roughly to field capacity and wilting point (*89*):

		Percent of ovendry weight		
	Number of soils analyzed	*Plastic limit*	*0.06 atm.*	*15 atm.*
Soil types:				
Clays, silty clays, and silty clay loams	11	23	29	18
Silt loams	27	23	31	10
Loams and sandy loams	11	20	27	10

In effect, this indicates that maximum compaction can be achieved without the soil being soaking wet—provided loads are heavy enough.

The effect of compaction on a dry soil has already been given some attention. In dry soils the resistance of the particles to rearrangement is great, for the thin water films provide little lubrication. Also, the effect of surface tension is pronounced so that the stress is partially neutralized. The addition of moisture improves lubrication and neutralizes the surface tension force so that compaction is easier achieved. With further increases of moisture, a critical point is reached at which a maximum of the smaller particles have been forced into the voids between the coarse grains, and the bulk of the remaining pore space is filled with water, leaving usually about 4 percent volume of air. At this point the soil has reached its maximum density. Further addition of water only provides an excess which, because it cannot be driven out by the compacting force, serves to reduce the density of the soil (*7*). Li has pointed out that the optimum moisture content that corresponds to the point of maximum solid substance of a soil type is that for one compactive pressure or one compactive effort only. Each compaction pressure has its own optimum moisture content (*45*).

Some fundamentals of the effect of moisture content on compaction and interrelations with stress and texture are shown in figure 3 from a series of papers by Proctor (*64*). Figure 3,*A* shows the effects of three degrees of stress on density. The greatest density from the heaviest load occurred at a lower moisture content than did peak densities from the lighter loads. Peak densities under light and medium rollers are greater than densities under the heavy roller below 8 percent moisture content.

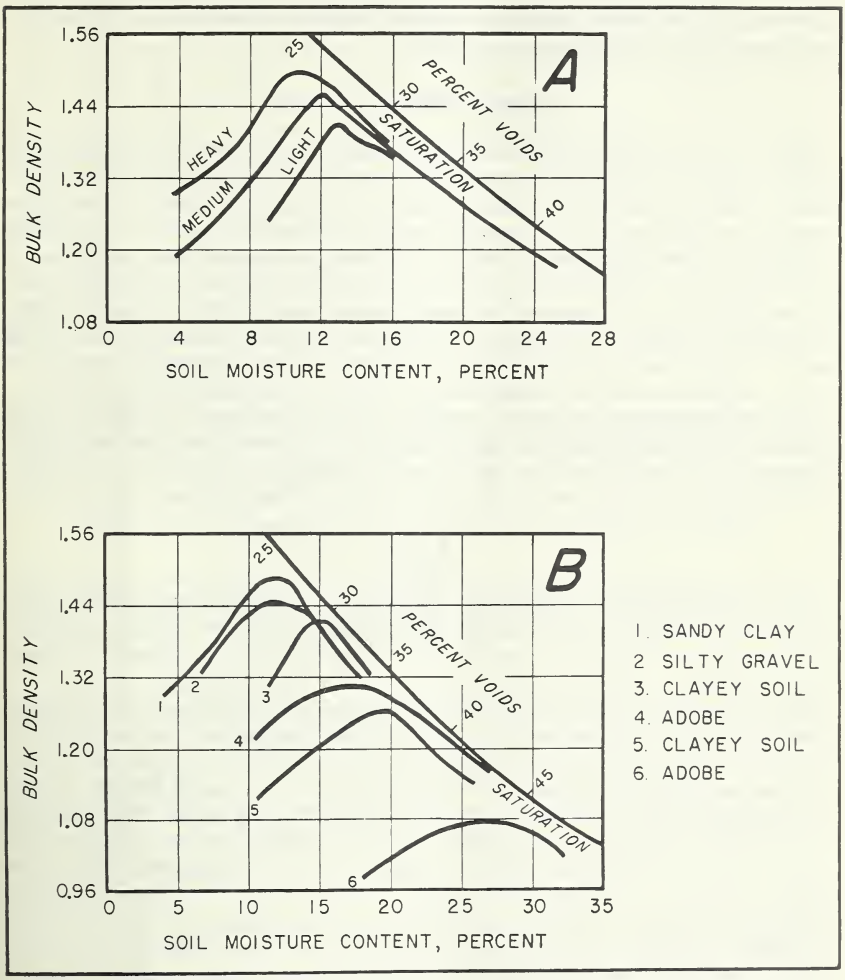

FIGURE 3.—Basic relationships between compaction and soil moisture content as affected by *A*, load, and *B*, soil texture (*64*).

From this Proctor concludes that ". . . proper moisture control with light equipment may give results superior to those obtained from very heavy equipment without proper moisture control." Restated from the viewpoint of this report, the same amount of damage can be inflicted on wet soils with light equipment as on much drier soils with heavier equipment. The zero air-voids curve shows the densities and moisture contents at which saturation is achieved. Percentages of

voids in the soil for various dry weights are given along this curve. As was noted above, no compaction method is able to attain a condition of complete saturation.

Figure 3,*B* shows the compaction-moisture content relationship for six different soils. The peak of the compaction curve for the adobe is reached with a much greater moisture content than for the sandy clay. Proctor attributes this to the larger proportion of fine particles in the soil, which require more water to lubricate this larger total surface area sufficiently to get maximum compaction. Also, notice that the less dense the soil, the greater the moisture content required to reach maximum density. And notice that the greatest densities are attained with soil possessing both sand and clay particles.

Organic-Matter Content

The amount of organic matter in the soil influences the amount of compaction possible and also determines the moisture content at which maximum compaction occurs. The greater the content of organic matter, the smaller the maximum compaction and the greater the moisture content required for maximum compaction.

Free, Lamb, and Carleton (*22*) show for Honeoye silt loam that an increase of bulk density from 1.47 to 1.61 was associated with a decrease in organic-matter content of 4.1 to 2.5 percent and a decrease in moisture content at maximum compaction from 26.0 to 22.0 percent. Similar results were obtained on three other soils. Compaction was also related to erosion; i. e., the greater the erosion, the less the organic matter and the greater the density at maximum compaction.

An interesting aspect of organic matter is the cushioning effect of forest humus and litter, which may offer the underlying soil some protection from compaction. However, this material may be too thin and not strong enough in texture to resist a strong traction torque, such as that required for starting a tractor in motion (*17*).

Frost

Frost both affects and is affected by compaction. Its effect on soil density can be to increase it: when water-stable aggregates are broken down by frost, they puddle the soil and increase its density (*74*). Frost action in compacted soils may loosen them.

Three European references show how compaction may reduce frost damage. Keen (*37*) has noted, for instance, that the consolidation of soil around plant roots by rolling counteracts the loosening action of weather alternations on soil structure and gives young plants a firmer foothold. In a recent English abstract of a Hungarian paper, the point is made that the lowering of soil temperature by radiation may be mitigated by operations such as rolling that lead to soil compaction; loosening the soil should be avoided when frost is expected (*84*). In an English abstract of a recent Polish paper, it was reported that because of trampling, grazed pastures are less susceptible to frost damage (*30*). In areas of peat soil, decline in yield of grasses after a very cold winter was believed attributable to root damage caused by rising of upper frozen layers. Heavy rolling of meadows or peat bogs was suggested as a means of reducing damage.

These observations probably relate to situations where stalactite frost is formed. Where concrete frost has been observed, compacted soils tended to freeze more readily, deeper, and harder.

Duration of Compaction Effects

How long the effects of compaction persist in a soil is largely a matter of conjecture. Parker and Jenny (*59*) found that the effects of compaction, as measured

by changes in infiltration rates, disappeared in about 5 years after planting the compacted area to mustard. On the other hand, there is clear evidence of the persistence of compaction in still-visible wheel tracks made over a hundred years ago by pioneers' wagons crossing western deserts.

In the Pacific Northwest, the percolation rate, detention storage, and retention storage of the upper 3 inches of soil in young second-growth Douglas-fir stands tend to increase with time elapsed since logging and burning. Most improvements appeared to be gained during the first 20 to 25 years.[9]

Garner and Telfair (*24*) employed an interesting technique of burying puddled soil sample cores in the soil at various sites and various depths and examining them periodically for changes in structure. Their results indicated some of the factors involved in rehabilitation of compacted soils. A rapid structural restoration within 1 year or less took place under cultivation, under sod, or in the presence of high organic content. Slower changes occurred in cores low in organic matter and in sites, such as dense woodlands, where the forest cover apparently insulated cores from volume changes resulting from moisture and temperature variation.

Considering the rearrangement and interlocking of particles that result from compaction, it is not difficult to believe that in dry climates the effect would persist for a long time. Smaller particles forced into the voids probably would remain in that position because there would be no force that would cause them to resume their original position.

Under wetter conditions, imbibition and swelling of fine-textured soil reduces density. Freezing and thawing (with the concomitant 9 percent change in volume of moisture) would also be a factor in loosening compacted soils. Fine-textured soils would be most affected because of their greater capacity for water storage.

Effect of Compaction on Soil-Water Relations

The few data available on the effects of logging and trampling on soil-water relations have indicated that they are major and of greater magnitude than are the changes in density. Brief attention will be given to a few studies that furnish correlative data.

Infiltration, soil density, and porosity of 68 soils, representing 39 soil series and varying in texture from sand to clay, were determined by Free, Browning, and Musgrave (*21*). As would be expected, a high correlation between bulk density and porosity was found: -0.99. Correlation between infiltration and bulk density (-0.24) and total porosity (0.24) were considerably smaller, though both coefficients were statistically significant at the 5-percent level. Correlation between infiltration and noncapillary porosity was higher (0.36), showing that the volume of this type of pore space is more closely related to infiltration than is total porosity.

The authors also found that an increase in noncapillary porosity of approximately 6 percent in a depth of 16 inches gave an increase in infiltration of 0.6 inch per hour. The correlation coefficient between aggregation and infiltration was 0.30 and between organic matter content and infiltration was 0.50. These relatively low coefficients indicate the considerable variation in infiltration that was encountered. Correlation is more evident when a soil is compacted over a range of densities, and the effect of each on infiltration is determined.

This was done in a study by Free, Lamb, and Carleton (*22*) to determine the effects on permeability of two levels of compaction at different moisture contents. Cores of Honeoye silt loam were compacted by dropping weights to apply forces of 17 and 51 foot-pounds; permeability of the cores was determined by noting the

[9] See footnote 3, p. 5.

time required for 0.4 inch head of water to disappear. This ranged from 1 minute to 192 hours, tending to increase with increase in soil density (fig. 4). Application of 51 foot-pounds of force to soil at higher moisture contents was associated with decreases in both density and permeability.

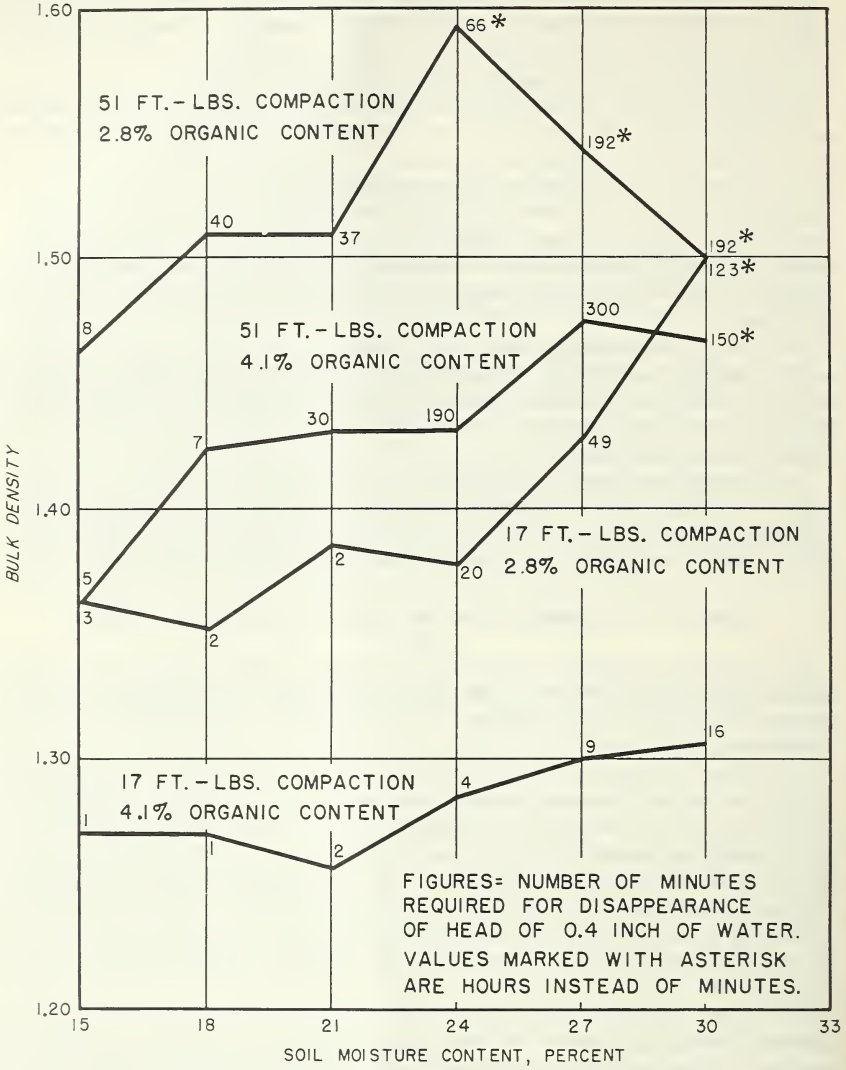

FIGURE 4.—Influence of soil moisture content, compaction, and organic content on bulk density and permeability (*22*).

For noncohesive soils the following equation has been given for permeability (*50*):

$$\text{Permeability} = \frac{e^3}{(1\text{-}e)^2}$$

where e denotes voids/total volume. By inserting typical values for loose and dense sand, with the relative permeability of the former taken as 100, the following results were obtained:

Condition:	Percentage voids ($e \times 100$)	Bulk density	Relative permeability
Loose	47	1.08	100
Dense	35	1.32	37

Effect of Compaction on Vegetation

Compaction sometimes increases the growth of vegetation and under other conditions may retard growth. Keen *(37)* believes that compacting the soil around plant roots by rolling makes it easier for the plant to obtain moisture and in addition makes more water available per unit volume of soil and gives the plants a firmer root hold. Heath *(28)* found that growth and development of cotton on compacted soil was much more rapid than on uncompacted soil. He attributed the better growth to the additional plant nutrients per unit volume of soil, and to the additional moisture. Further, he believed that a greater nitrogen supply was available to the plants because of the reduction of microflora population in the compacted soil as a result of poorer aeration.

For a sandy loam rangeland soil, Hyder and Sneva report that rolling the seedbed provided advantages in moisture retention, rate of seedling emergence, seedling growth, survival, lateral root distribution, and occurrence of root hairs near the surface. An undisturbed soil was concluded to represent near-optimum soil density. A roller weight of 400 to 500 pounds per foot of axle provided satisfactory firmness in a plowed seedbed *(33)*.

On the other hand, Doneen and Henderson *(12)* have noted that soil compaction sometimes limits root development and reduces growth of vegetation. Here inadequate water supply from restricted water penetration is a closely associated factor. J. F. Lutz *(48)* observed that excessive packing of the montmorillonitic type of clay reduces pore size to such an extent that no water or air is available to plant roots. Swanson and Jacobson *(82)* reported a range of corn yield from 20 to 100 bushels per acre from a fine sandy loam compacted by various cultivation treatments; corn yield was inversely proportioned to soil hardness. Cultivating to break the surface crust formed by rainfall impact increased yields substantially.

The contradictory effects of compaction on growth probably stem from differences in the amount of compaction in relation to aeration and moisture supplies. Where moisture is limiting and aeration adequate, a certain amount of compaction may be beneficial by increasing moisture content per unit volume of soil. Beyond that point, the soil may become so dense that movement of moisture to the plant is restricted. In the majority of medium- to heavy-textured soils, compaction reduces aeration and is detrimental to plant growth. According to Steinbrenner,[10] the major effect of compaction in the Pacific Northwest is a reduction of macroscopic pore space, which greatly reduces tree growth.

Reproduction is not readily established on compacted soils. Steinbrenner and Gessel found that growing conditions on skidroads in cutover Douglas-fir were so poor that seedlings became established only with difficulty, and those of poor quality rapidly succumbed. Over three times as many seedlings became established in the cutover area, 1,260 per acre, as on the skidroads, 410 per acre *(80)*.

Pomeroy *(63)* reported that while the disturbed condition of surface soil due to logging provided good contact for loblolly pine seed and gave germination rates of over 90 percent, about 60 percent mortality on clay loam soils and 27 to 29 percent on loamy and sandy soils resulted because the radicles were unable to penetrate the compacted soil surface. Likewise, Korstian *(40)* has observed that radicles of acorns were unable to penetrate soils that had been excessively compacted. Pearson and Marsh *(60)* noted in the Southwest that trampling and log-

[10] See footnote 3, p. 5.

ging in wet weather accentuated the compact structure of clays, making conditions unfavorable for reproduction of ponderosa pine. Possibly seed may be damaged by compacting forces: seeds are particularly susceptible to mechanical damage when relatively dry and brittle or when they are just about to germinate *(46)*.

Roots cannot penetrate highly compacted soils. It has been found that sunflower roots, for instance, cannot penetrate soils that have compacted to densities ranging from 1.75 for sands to 1.46–1.63 for clays *(90)*. Doneen and Henderson *(12)* found that corn roots were unable to penetrate compact subsoil of Yolo clay loam with a bulk density of 1.5. Generally, root growth tends to be restricted in fine-textured soils when the bulk density gets much above 1.4 and in coarser textured soils above 1.6 *(65)*.

Pot experiments with sugar beets have shown that root development was restricted at noncapillary porosities of 3.5 percent in sandy loam and 11.7 percent in silt loam. Root development was good at porosities of 14 and 18 percent, respectively. Soils compacted to a density of about 1.95 were not penetrated by roots; at a bulk density of 1.8 the main taproot penetrated the soil but there was little feeder-root development. At 1.5, root penetration and distribution were unrestricted *(62)*.

Forristall and Gessel *(18)* have noted that the high density of hardpan layers impedes root growth and determines effective root depth. Of some significance were observations that the critical density differed for different species: western redcedar grew on a wet site with a bulk density of 1.80; a density of 1.50 stopped the growth of red alder roots; and Douglas-fir and western hemlock root growth was restricted when the bulk density approached 1.25.

H. J. Lutz *(49)* and Meinecke *(53)* have cited instances of the killing of roots by soil compaction in public parks. Heavy woodland grazing in North Carolina reduced growth rate of yellow-poplar 50 percent, hickory 30 percent, and red maple 27 percent, reductions which were attributed to the effects of compacting the upper 6 inches of soil *(34)*. Olson *(56)* has pointed out that in the western white pine type, underground damage to roots by mechanized logging may be one reason for the poor growth and condition of partially cut stands. Five years after logging, damage may be sufficient to nullify the silvicultural aims of the cutting. McCulley *(51)* attributed decline in vigor and mortality of loblolly pine seed trees in coastal North Carolina to wet-weather logging that churned up the heavy, poorly drained soils. Logging poorly drained areas in moderately dry weather did not harm the trees.

Fountaine and Payne *(19)* noted that the growth of mustard in heavily compacted areas was obviously stunted as compared with growth on uncompacted plots. No roots were found in clods of soil with less than 38.7 percent pore space. Wheat roots were found in clods containing only 30 percent pore space.

Merz and Finn *(54)* have observed that young plantations on graded strip-mined lands in Ohio had poorer survival and growth than plantations on ungraded areas. Compaction by heavy grading equipment was considered to be the cause. Ring infiltrometer rates on graded banks averaged 17 inches per hour as compared with 178 inches for ungraded banks; mean volume weights were 1.06 and 0.96.

Dambach has found that grazed sugar-maple woods in Ohio produced one-third less maple syrup than protected woods. *(9)*.

Discussion

Certain generalizations as to the influence of compaction and the factors affecting it can be made. But no more than generalizations are possible: even though there are few instances where contradictory results have been obtained, the wide

range of soil and cover conditions in the few studies that have been made, and differences in research procedures used, have produced variable results.

The mechanics of the compaction process, viewed without regard to causative agent, have been better defined. But in this too the information resides more in a set of principles than in quantitative data. Some of the important principles are:

- The amount of compaction will depend on the degree to which the stress applied to the soil overcomes the resistance the soil offers to deformation.
- The resistance that the soil offers depends on its moisture content, texture, structure, density, and organic content.
- As this resistance is overcome, the effect is to pack individual soil particles closer together and to crush soil aggregates, thus reducing pore space.
- Resultant additional solid materials per unit volume increase the resistance of the soil to deformation to a point where resistance and stress are in equilibrium and no further compaction occurs.
- As soil-mosture content increases, resistance to stress decreases and compaction can be achieved with progressively reduced loads.
- Maximum density is obtained at a moisture content about midway between field capacity and wilting point.
- Increasing moisture content beyond that point further lowers the resistance to compaction and reduces the maximum density.
- Soils that have the greatest range of particle-size (i. e., medium-textured soils) compact to greatest densities, finer particles filling the voids between coarser particles.
- The less dense the soil, the greater opportunity for compaction.
- The greater the organic content, the smaller the maximum compaction and the greater the moisture content required for maximum compaction.
- Soil freezing tends to compact soil by breaking down water-stable aggregates and tends to loosen compacted soils.
- Duration of compaction depends largely on the stresses the soil undergoes by swelling and shrinking from changes in moisture content and temperatures.
- Compaction increases bulk density, reduces total pore space by the same proportion, reduces noncapillary pore space a greater amount, and has its greatest effect on infiltration and percolation.

Logging Operations

As has been noted, the compaction resulting from a logging operation can depend on the type of equipment, area disturbed, frequency of travel, and such site factors as soil texture and moisture content. The relative importance of these factors, in respect to minimizing or reducing compaction, varies.

For instance, weight of equipment used may not be an important factor considering the pronounced compactive influence of relatively small ground pressures. Crawler tractors, with smallest ground pressures, can have a major effect on the soil. Under wet conditions, for instance, one pass with a tractor has been known to reduce macroscopic pore space by half and infiltration rate by 80 percent *(78)*. In another instance, two passes with a tractor reduced the infiltration rate from 1.4 to 0.6 inches per hour *(12)*.

However, differences in weight of equipment may have an important effect on the depth of soil compacted and thus, perhaps, on its duration.

The importance of frequency of travel is limited because maximum compaction is achieved with a few tractor trips. Soil-moisture content can be an influential factor; however, vagaries of weather during a logging operation will normally yield sufficient rainfall to achieve ultimate compaction. Possibly the factor influencing compaction that is most susceptible to management is the area of disturbance; this in turn will depend, among other things, on the intensity of the cut.

Logging Compaction Control

The simplest way to control compaction, like erosion, is to prevent it. But a certain amount of compaction is associated with any use of forests or ranges; how much can be prevented is the question; and it will remain one as long as the overall effects of compaction on soil and water conservation and site quality are unknown.

It appears doubtful that the area over which travel must take place can be reduced much below 10 to 20 percent in tractor logging; Steinbrenner believes it should be possible to reduce tractor skidroads to 10 percent or less of the logged area in the Douglas-fir region.[11] With the drastic effects on soil properties observed, compaction of this area should have a major influence on runoff and erosion.

Areal disturbance and compaction may be reduced by the use of high-lead yarding, which offers one advantage over tractors in that uphill yarding tends to fan out and spread runoff water. Tractor yarding is almost always downhill and thus concentrates runoff water *(70)*. Employment of the Wyssen skyline method offers the least damaging system, but it is adapted only to mountainous areas.

A ready means of reducing areal disturbance is to plan road systems before the logging operation begins rather than during the operation. In this connection, research is needed to determine, for given conditions, the combination of road system, skidding system, and equipment that will give the lowest areal disturbance. Also needed are studies to determine the relationship of areal disturbance to intensity of cut.

In northern latitudes, over-snow hauling rather than over-soil hauling can reduce soil compaction.

Trampling

Trampling by livestock compacts the upper 6 inches of soil and exerts pressures equivalent at least to those of heavy tractors. On the basis of static ground loads, cattle exert a greater compactive effect than sheep. Studies indicate that trampling reduces infiltration and percolation as much as logging equipment does.

Little is known about area disturbed by trampling in relation to number of stock. Possibly, where trampling is an important factor, a sharp reduction in stock numbers would be necessary to reduce trampling to any beneficial extent.

The effect of trampling on soil compaction and soil-water relations will not be understood until elementary studies have been made on the trampling process, proportion of grazing areas disturbed, effects on infiltration and runoff, and their duration.

Reduction of Trampling

Trampling compaction may be reduced by following common-sense principles. Keeping sheep and cattle off western mountain ranges during the spring mud period would be helpful, as would bedding out (the use of different bedgrounds on different nights, instead of returning again and again to the same bedding grounds). Regulatory practices, as described by Ellison, also provide for better distribution of cattle by salting, developing watering places, and fencing; protecting certain critical areas from grazing altogether, and reducing size of herds *(15)*. As degree of compaction is influenced by organic-matter content, overgrazing, which removes most of the litter source, should be avoided.

Certainly range management to minimize compaction must require rather del-

[11] See footnote 3, p. 5.

icate adjustments. Minimum compaction occurs on well-vegetated ranges, but it is difficult to visualize livestock trampling without some consumption of cover. What is needed is an animal that can graze with its feet off the ground.

Rehabilitation of Compacted Soils

Little is known about how to break up compacted layers in forest and range soils. In the Douglas-fir region Steinbrenner and Gessel used a D-6 tractor with a toothed blade to break up compacted soil of skidroads to a depth of 18 inches. A towed heavy farm disk broke up the large clods. Cost of this operation was $3.50 per acre *(80)*.

Some types of vegetation can penetrate dense soil. A study in California provides one example *(59)*. After Ramona loam was compacted by excessive tractor use in both a wet and dry condition, mustard was sowed annually on the compacted plots and cut off in the fall, and infiltration was measured. In 5 years the dry plot had nearly recovered its original infiltration rate. Rates on the wet plots also increased markedly.

According to a Russian paper *(73)*, deep loess soils, compacted at depths from 15 to 40 centimeters, were rapidly loosened and their permeability increased by growing alfalfa. In this country, alfalfa, sweetclover, and sericea have been suggested as crops that might be useful in improving subsoil conditions *(94)*. Laws *(43)* noted that under deep-rooted legumes in black clay the formation of an indiscriminate mud-crack pattern may be helpful in breaking up a compacted layer.

Seeding of areas, denuded by logging, with perennial grasses has been successful in Washington and Oregon if accomplished within a year after logging. Results were not good on areas that had been denuded for more than 1 year *(27)*. Trimble and Weitzman *(88)* have reported successful revegetation of logging roads in West Virginia by seeding of chaff and by liming and fertilizing.

On an experimental basis, explosives have been used in the Belgian Congo to loosen heavy compacted clays prior to planting with eucalyptus. Results have been encouraging but costs are high *(11)*.

Conclusion

Soil compaction is a universal process associated with any use of forest or rangelands. Its major effect is to drastically reduce the pore space through which water moves into and through the soil, thereby reducing infiltration and percolation, increasing surface runoff, and encouraging erosion. These effects do not require heavy and repetitious travel. Under wet soil conditions normally encountered, even the lightest of vehicles or light-footed trampling can effectively compact the soil.

The present-day trend toward more intensive use of our forest and range lands will undoubtedly involve not only more frequent travel but the use of heavier mechanized equipment. This could have serious effects not only on soils but also on streamflow, and perhaps, on site quality. At the same time, it is evident that considerable soil compaction has always occurred: our second- or third-growth forests provide evidence of considerable soil disturbance that occurred during past logging operations; and livestock trampling is not new—perhaps the greatest of trampling forces was the soil-pounding buffalo herds. Thus our forests and ranges have survived past soil compaction. Whether their present condition has been influenced by it is not known; nor can one predict the potential compaction from future more intensive use.

The conclusion from this review is that soil compaction on forest and range lands is a subject that merits intensive research. All phases of the subject beg for

study: The compaction process; the extent of compaction in relation to forest and range harvesting methods; the effects of compaction on soils, erosion, surface runoff, streamflow, and site quality; and remedies for compaction and methods of preventing or minimizing it.

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