

SOIL DISTURBANCE AND COMPACTION IN WILDLAND MANAGEMENT

Part I - Principles and Review

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Part II - Management Considerations

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Introduction

The major soil parameters affecting plant productivity are structure, rooting volume, drainage, and fertility. Management activities which cause soil deformation modify soil structure and thus affect productivity. The effects may be either beneficial or detrimental and they can be very important for plant production. Tillage is a kind of soil deformation practiced for its benefits. However, most of the soil deformation experienced in wildland management is detrimental; it tends to diminish the productivity of forest, range, and recreation lands.

Lateral displacement, compaction, puddling, and consolidation are all different kinds of soil deformation. I will address all but consolidation, which is an engineering consideration most important in dealing with foundations for permanent structures.

There is a large volume of literature on soil compaction. A bibliography subcommittee of the soil compaction committee of the American Society of Agricultural Engineers compiled an annotated bibliography of 600 articles about 1958. Also, Lull (1959) authored a very good review of the literature on soil compaction for wildland management. Several reviews on soil compaction and plant responses have been published more recently, generally of more limited scope than Lull's review; for example, Vomocil (1957), Rosenberg (1964), Barley and Greacen (1967), Liddle (1975), Chancellor (1976), Cannell (1977), Greacen and Sands (1980), Soane et al. (1981, 1982), Ruark et al. (1982), Byrnes et al. (1982), and Froehlich (1984). I will add to Lull's review, explaining the main concepts and some of the consequences of soil deformation. The engineering literature is so extensive that only a few of the more pertinent articles are included in the bibliography. Much of the engineering literature has been reviewed by Gill and Vanden Berg (1967) and in the 9 chapters of *Compaction of Agricultural Soils* edited by Barnes et al. (1971).

The following text contains some paragraphs which are more technical than most of the manuscript, or are difficult to follow without a technical background. Lines are single-spaced in these paragraphs. They can be skipped without detracting from the rest of the manuscript.

Summary

A. Soil and its deformation. Any unconsolidated material at the surface of the earth is considered to be soil, unless the material is artificial or >90% (weight) of the material is coarser than 2 mm. Soils are not homogenous, because randomly distributed particles in them are rearranged by natural forces within soils. Soil structure, or particle arrangement, is maintained by cohesive forces between particles. External stresses (stress = force/area) deform soils when the resulting forces are greater than the sum of cohesive, adhesive, and frictional forces within soils. Soil water is important at lower contents due mainly to adhesion and at higher contents due mainly to the redistribution of stresses. By reducing the forces between particles, water reduces frictional forces and thus decreases soil strength. With less strength a soil is more easily deformed. Soil consistence is a measure of strength. Noncohesive soils are loose, although to engineers "noncohesive" is a broader category of soils. Strong cohesive soils are hard when dry, firm when moist, or stiff ("plastic") when wet. Weak cohesive soils are soft when dry, friable when moist, or nonplastic when wet.

B. Natural soil density and porosity. Soils are about half solid particles and half pore space between the solid particles. Surface soils generally have more porosity than subsoils. Densities of the solid particles average about 2.65 Mg/m^3 , or about 1.37 Mg/m^3 for organic particles. The density of a volume of soil including both solid particles and interparticle pore space is called bulk density. It ranges from 0.2 Mg/m^3 or less for organic soils to about 2.0 Mg/m^3 in very dense subsoils or compacted till. Surface soil bulk densities are commonly on the order of 1.0 Mg/m^3 and subsoil bulk densities are commonly about 1.2 to 1.5 Mg/m^3 . Coefficients of variation for both surface and subsoil densities are generally on the order of 10 to 15%, although some investigators have reported coefficients greater than 20%.

C. Measurement of deformation. Compaction, puddling, mixing, and lateral displacement are different forms of soil deformation. Soil strength is the resistance to deformation. Cone penetrometers are commonly used to assess soil strength in the field. Compaction is a decrease in volume. It is assessed most directly by measuring the bulk density, which is the weight per volume of soil. It may be assessed indirectly by measuring soil permeability or infiltration rates.

Methods of measuring soil bulk density:

Core - The most direct method, simple; but cores cannot be driven into gravelly soils nor into soils with many roots.

Clod - Applicable to all except noncohesive soils; clods are generally coated with paraffin or saran for immersion in water to determine volumes.

Irregular hole - applicable to all soils; excavated holes may be filled with sand or styrofoam beads to determine volumes.

Transmission of gamma radiation - applicable to all except very gravelly soils and organic soils, but soil water content must be determined to convert moist bulk density to dry bulk density.

D. Management induced deformation. The area of soil disturbed ranges from nil in aerial logging operations to 100% in tilled seed orchards and in some conversions of brushy rangeland to grass. Soil disturbance generally covers about 20 to 50% of an area in clear-cut tractor logging and soils are noticeably compacted in about half of the disturbed area. Undisturbed bulk densities are generally increased 10 to 80% in skid trails. Most of the increase is caused by the first 3 to 6 round trips. Soil macroporosity and infiltration rates are markedly affected by less trips. Site preparation for planting may cause more soil disturbance than harvesting operations, but compaction is generally not too great where small tractors operate over litter-covered soil. Animals exert as much, or more, stress on soils than tractors; however, they compact soils less deeply. Nevertheless, compaction by grazing animals may reduce infiltration enough to increase runoff over the ground surface. Compaction by people is serious in many campgrounds. Off-road vehicles and horses generally cause more disturbance along trails and more soil compaction than do hikers.

E. Predicting Deformation. The susceptibility of a soil to displacement or compaction increases as its strength decreases. If management operations are about to commence, predictions of compaction may be based on cone indices obtained with a cone penetrometer or based on any other index of soil strength. Long-range predictions of soil compaction must be based on soil properties and soil water content expected for the date that management operations are scheduled to occur. The important soil properties are texture (particle-size distribution, PSD), particle shape, particle composition, the clay fraction and its chemical environment, organic matter content, particle arrangement and aggregation, and in some cases cementation. Particle-size distribution has received the most attention, but it is not nearly as important as organic matter

content. Sandy loam, and possibly sandy clay loam, soils tend to have the highest bulk densities in undisturbed states. Bulk densities are greatest for poorly sorted, or well graded, materials. The relative (percent) increase in bulk density upon compaction is about the same for soils of any texture. Sandy loams or sandy clay loams, are still the heaviest after compaction. Small amounts of water increase the strength of noncohesive soils. However, once the capillary pores are filled, larger amounts of water decrease the strength of soils. Soils are most susceptible to compaction at water contents near field capacity. Since water is practically incompressible, saturated soils are not susceptible to compaction. However, saturated soils are easily puddled or displaced, as in ruts.

F. Effects of Deformation. Lateral displacement of soil can have dramatic effects on productivity and the hydrologic regime, due to the removal of surface soil with more organic matter and the exposure of denser subsoil. The effects of soil compaction can be dramatic too, but they are generally less severe than lateral displacement. Root penetration decreases as soil strength increases and aeration decreases in compacted soils. The root growth of most species is completely stopped at bulk densities from about 1.4 Mg m^{-3} in clayey soils to about 1.8 in sandy soils. Restricted root growth reduces top growth and yield, unless the soils are moist in the root zone throughout the growing season and so fertile that plenty of nutrients can be obtained from a relatively small volume of soil. The height growth of young trees may be reduced by one-third. Reductions in yield or the volume of bole wood may be considerably greater. In the most compacted part (mean bulk density = 1.12 Mg m^{-3}) of a plantation with 15 year old ponderosa pine trees on Aiken loam, the volume per tree was 21% less than in the least compacted part (mean bulk density = 0.83 Mg m^{-3}); however, the total volume was 59% less in the most compacted part due to less trees in addition to less volume per tree.

G. Reduction of Compaction. The natural structure of disturbed soils may be restored by shrink-swell due to drying and wetting, by frost action, and by biotic activity. Recovery to undisturbed bulk densities may require only a few years where the natural processes of amelioration are most active and compaction is not too deep to decades or centuries where the processes are least active. Recovery is particularly slow in nonclayey soils of warm climates, or even in cold climates such as in the Sierra Nevada and Cascade Ranges where a thick blanket of snow covers the ground throughout the winter. Recovery may be hastened by tillage, the addition of plant residues or other amendments, or a combination of tillage and amendments. Deep tillage prior to planting trees in compacted areas is effective for improving seedling survival and growth in many soils. Discing however, is least effective in the more compacted soils where the benefits of tillage could be greatest, because it is difficult for discs to penetrate deeply into compacted soils.

Richard Howard at different water contents (Fig. 5B). The soil mixtures compacted at similar water contents exhibit linear porosity-pressure loss relationships at higher porosities, but a linear relationship is hardly evident for soil compacted at different moisture contents. A nonlinear total porosity-pressure loss relationship does not necessarily invalidate Steimbrenner's hypothesis of linear macroporosity-pressure loss relationships but could be due to nonlinear macroporosity-total porosity relationships.

The total porosity-pressure loss relationships are not nearly as good for field compacted soils as they are for sieved mixtures. Natural soils have many more complex pore spaces compared to all simple packing voids in the remolded soils. The air permeameter cannot be used in noncohesive soils nor in soils of very low density unless they are cemented, because the 100 kPa pressure will displace soils with little strength.

D. Management Induced Deformation

1. Areal extent of disturbance

The area over which soils are disturbed in land management varies from practically 100% for annual crop land to possibly less than 1% for some extensively managed timber land which is harvested by helicopter or balloon logging techniques. As the detrimental effects of disturbance on soils and their productivity become more universally apparent, there is a trend toward less disturbance. Conservation, or minimum, tillage increased from less than 3% of the harvested cropland in the United States in 1965 to more than 16% before 1980 (Larson and Osborne, 1982). By 1978, about 20% of the corn and soybean crops in Kentucky were no-tilled. Although the statistics are not as dramatic in forestry, there is a trend toward more planning of skid trails in order to minimize tractor traffic in partial cutting and thinning timber (Bradshaw, 1979, and Froehlich et al., 1981), and more stands on only moderately steep slopes are being harvested by cable rather than by tractor. It is more difficult to demonstrate the detrimental effects of soil disturbance on timber than on annual crop production; not necessarily because the effects on timber production are any less than those on annual crop production, but due to the problems involved in estimating the productivity of timber land.

Tillage is a planned disturbance. Disturbances by off-road vehicles (ORVs) and grazing animals are generally unplanned, although the main travel routes can be controlled. Rutting and puddling of wet soils, and lateral displacement of dry noncohesive soils, are sometimes greater problems than soil compaction by ORVs. Although roads, landings, and sometimes even skid trails may be planned, much of the disturbance in timber harvesting is unplanned. Site conversions of relatively unproductive plant communities to timber species or forage plants may involve disturbances in the removal of undesirable plants and preparation of seed beds.

Steinbrenner and Gessel (1955) found that in tractor logging of clearcut areas in western Washington 26% of the area was covered by skid-trails. Wooldridge (1960) found in north-central Washington that tractor logging disturbed 29% and skyline logging disturbed 11% of the ground surface. Tractor logging disturbed the soil beneath the surface litter cover in 22% of the area, but soil disturbance occurred in only 5% of the skyline logged area (Wooldridge, 1960). Skyline cable logging disturbed less than 10% and severely disturbed less than 3% of the surface soil in an area of West Virginia (Patric and Gorman, 1978). Dyrness (1967) found much more disturbance from skyline logging in the H.J. Andrews Experimental Forest, Oregon. Soil was disturbed in 40% of the high-lead logged area and soil disturbance was nearly as extensive in the skyline logged area. However, disturbance was generally deeper and considerably more severe in the high-lead logged area. Tractor logging in the same Experimental Forest disturbed 64% of the area and the area of compacted soil was much greater than with high-lead logging (Dyrness, 1965). Garrison and Rummell (1951) found less soil exposure from horse logging than from either tractor or cable logging. Hatchell et al. (1970) investigated logging disturbance in nine areas on the Atlantic Coastal Plain. They found 12 (3 to 23) percent of the area in primary skid trails, 20 (9 to 42) percent in secondary skid trails, and 1.5 (0.3 to 5) percent in log decks.

Haupt (1960) estimated soil disturbances during partial cutting of ponderosa pine stands in Idaho. He found that the aerial extent of disturbance was directly proportional to the amount of timber harvested. The area disturbed ranged from 5% to 18% in single tree selection and to 13% in group selection.

Froehlich et al. (1981) investigated the effects of designated skid trail systems. They found that skid trails covered 20% of the area in conventional thinning, 11% with trails 100 feet apart, 7% with trails 150 feet apart, and 4% with trails 250 feet apart.

There are many more data on ground disturbance in logging, but these are enough to indicate the wide diversity of results obtained with different equipment, operators, and logging techniques in timber stands of different composition in different types of terrain with different soils. Added to all these variables are different methods of investigating and reporting disturbance. Most of the methods are visual and somewhat subjective. Bulk density measurements are more quantitative but generally too time consuming for the large numbers of samples required to obtain statistically significant results. The Steinbrenner air permeameter is useful for estimating both the extent and severity of soil disturbance and compaction. Readings are quick and quantitative. However, large numbers of readings may be required to differentiate between undisturbed and disturbed and compacted soils, due to the large variance of readings within an undisturbed area.

A.G. Sherrell, B. Wickman, and K. Lanspa used a Steinbrenner air permeameter to determine the extent of compaction in 10 tractor and one skyline logged areas of the Pacific Southwest Region, Forest Service, USDA. They found that the soil in 25 to 48% of the tractor logged areas was visibly disturbed and that 13 to 31% was compacted (Table 7). The criterion for compaction was an air permeameter reading greater than 11.6 psi (80.0 kPa) or, if the mean background reading in undisturbed spots was less than 5.2 psi (35.9 kPa), a reading greater than one-half the background reading plus 9.0 psi (62.1 kPa).

In desert areas, where the soils are usually dry and thus have comparable matric potentials, penetrometers are useful for estimating the areal extent of compaction. Adams et al. (1982) utilized a penetrometer to determine compaction by increases in soil strength on off-road vehicle trails and in areas of intense livestock use in the Mojave Desert, California.

Any exposure of mineral soil will subject the bared surface to compaction by raindrop impact. Tarchitzky et al. (1984) found that simulated rain increased the bulk density of a sandy soil from 1.42 to 1.74 Mg/m³ and that of a clayey soil from 1.35 to 1.88 Mg/m³. Since the compacted crust is generally less than one to a maximum of a few mm thick, the adverse effects are due largely to reduced infiltration and also to reduced exchange of air between soil and atmosphere.

Table 7. - Areal extent of soil disturbance and compaction from logging 11 timber sales in the Pacific Southwest Region of the Forest Service. Most of the soils were dry when the areas were logged -- only in one area were the soils wet, and there they were frozen in the mornings.

Logging Method*	Silvicultural Prescription	Area	
		Disturbed	Compacted*
Skyline	Overstory removal	22	3
Tractor	Overstory removal	25	14
Tractor	Overstory removal	44	21
Tractor & RTS	Overstory removal (wet)	36	14
Tractor & RTS	Commercial thinning	34	18
Tractor & RTS	Intermediate sanitation	43	22
Tractor & RTS	Intermediate sanitation	33	13
End-lining	Overstory removal	28	19
FMC	Overstory removal	48	15
Tractor	Partial cut	43	26
Tractor	Clear-cut	43	31

* Tractor refers to skidding by crawler tractors. RTS = rubber-tired skidder. End-lining means that logs were winched to designated skid trails in order to limit the area traversed by tractors.

2. Timber management

a. Harvest

Wherever litter has been displaced in timber harvesting to expose bare soil there is most likely some soil disturbance and generally at least some soil compaction. Organic litter cushions the effects of timber harvesting. When tractor traffic or logs displace the litter they impact the soil directly. The impact is obvious if soil has been displaced, but compaction is seldom apparent visually. Compaction may be obvious if a tractor track or wheel has simply depressed the ground surface, but moving tractors and logs generally displace some soil laterally too. The displacement of soil is usually greatest where tracked tractors turn in wet or noncohesive soils. The forward ends of moving logs can gouge and displace considerable soil. If the forward ends are lifted off the ground, the logs may displace less soil but do more compacting.

There is surprisingly little difference in compaction due to different kinds of tractors used in logging. Froehlich et al. (1980) found that a rigid-track tractor caused slightly more compaction than either a flexible-track tractor or a rubber-tired tractor and soils were compacted to greater depth by the rigid-track tractor. The greater ground pressure of the rubber-tired tractor was more than offset by the greater weight and vibration of the rigid-track tractor. Mean soil bulk densities increased 11 to 20% in the uppermost 20 cm of soil, depending on the kind of soil, after 20 round trips empty and loaded with a rigid-track tractor. Mean water infiltration rates were reduced to 2.75 cm/hr under rigid-track tractor tracks and to 3.23 and 3.54 cm/hr under the flexible-track and rubber-tired tractor tracks (Cafferata, 1982). Infiltration rates were reduced less where the logs dragged, between tracks, than under the tracks for all but the rigid-track tractor skidding.

Air permeameter readings are generally more sensitive to the compaction of surface soils than are bulk densities. Helms (1983) delineated areas in a 15-year old plantation to separate stands in which most of the trees fell into one of two height classes. Surface air permeameter PI differences (-10.4%) from the area of taller trees to the area of shorter trees were greater than

mean soil bulk density differences (7.4%) in the uppermost 30 cm of surface soil (Table 8). However, the variability of air permeameter readings within each height class was greater, such that the difference in soil bulk densities between classes was more highly significant.

Table 8. - Mean soil bulk densities and air permeameter pressure losses (PI) in two height class areas of 15-year old ponderosa pine trees. The areas were delineated by Helms (1983) in a plantation of the Forest Hill Divide, California. There were 227 trees in the area representing taller trees and 196 in the area of shorter trees.

	Bulk Density				PI, Air Permeameter	
	4 Inch	8 Inch	12 Inch	Mean*	Surface	4 Inch
	g/cm ³				kPa	
Tree height class						
taller trees	0.894	0.917	0.934	0.915	33.5	25.9
shorter trees	0.966	0.987	0.995	0.983	30.0	22.3
Class difference						
absolute	0.072	0.071	0.061	0.068	-3.5	-3.6
percent	8.1	7.6	6.5	7.4	-10.4	-13.9
Standard Deviation	0.010	0.011	0.010	0.010	0.9	0.9
Student t	6.93	6.17	6.10	6.77	-3.82	-3.78

* Mean of all 3 depths.

In North Carolina, Gent et al. (1983) found that tractor logging increased mean soil bulk densities from 1.00 to 1.20 Mg/m³ in the surface 3 inches (7.6 cm) of soil. They found mean increases from 1.04 to 1.43 Mg/m³ in the surface and from 1.45 to 1.68 Mg/m³ at the 9-12 inch (23-30.5 cm) depth beneath skid trails. Relative (percent) decreases of both macroporosity and hydraulic conductivity in the surface (3-inch) layer were much greater than the relative

Increases in soil bulk density. However, hydraulic conductivity did not decrease in the 9 to 12-inch layer and the decrease of macroporosity was insignificant. The relatively small change in macroporosity at depth may be attributed to greater density and much less macroporosity in the 9 to 12-inch layer even before logging. With much less macropore space, a larger proportion of the density increase upon compaction at depth in skid trails was probably due to decrease in nonmacropore space, or pore space which has little effect on hydraulic conductivity.

Primary skid trails are much more densely compacted than minor trails with only one or two passes or round trips. Miles (1978) found that surface soil bulk density increases exceeding 0.3 Mg/m^3 , or about 40% greater than undisturbed surface soil, were common on the Blodgett Experimental Forest, California. He attributed relatively small amounts of compaction on minor skid trails to the presence of 6 to 8 cm of organic litter cover which was no longer present after several round trips on primary skid trails. Logging over drier soils produced less compaction than logging over wetter soils. As well as more compaction on wetter soils, Moehring and Rawls (1970) found that deep rutting and puddling of wet, undrained soils in Arkansas affected subsequent tree growth adversely. According to Froehlich et al. (1981), undisturbed soil bulk densities are generally increased by 10 to 80% in skid trails, depending on the soil water status among other variables. Campbell et al. (1973) found, in Georgia, that a rubber-tired skidder compacted Piedmont surface soils from a mean of 1.30 Mg/m^3 to 1.45 on secondary trails (two or more trips), to 1.51 on primary trails, and to 1.57 on log decks. Uphill skidding causes more compaction than downhill skidding (Sidle and Drlica, 1981).

Froehlich (1978) summarized more data on soil compaction in logging. According to Lull (1959), tractors seldom compact soils below 30 cm depth, although Parker and Jenny (1945) reported compaction to a depth of 60 cm in an orchard. Steinbrenner (1955) showed that the effects of surface soil compaction on macropore space, and particularly the infiltration of water, are much greater than the effects on bulk density. He found that it took 4 tractor trips during wet winter and 6 during dry summer logging to increase the soil bulk density

more than two-thirds of the maximum increase after more trips, but the infiltration of water was decreased more than 90% after two winter trips and nearly 90% after four summer trips.

b. Site preparation

After a stand of timber is clear-cut, the area is prepared for seeding or planting seedlings from a nursery. The minimum requirement for seeding is exposure of bare soil, because organic litter (or "duff") is not a favorable environment for the germination of seeds and the establishment of tree seedlings. If seeds are to be planted, rather than relying on natural dispersion from seed trees, the area may be cultivated.

The main objective in preparing a site for planting seedlings is to control or eliminate competitive vegetation. It is not necessary to expose bare soil, although organic litter is commonly removed to facilitate planting. Converting a site of less desirable tree species or brush generally requires more drastic means than preparing a clear-cut area for planting.

Some means of site preparation have little impact on soil. Cutting or crushing brush and applying herbicides has little effect on soils, unless it involves the operation of heavy equipment over bare soil. Broadcast burning of slash in a clear-cut area generally has an impact in proportion to the amount of the "duff" layer that is burned. The impact on soil escalates when tractors are used to remove stumps, doze brush, or pile slash. Stransky (1981) measured soil bulk densities at 10 cm depth, the depth of maximum compaction, after 3 site treatments following clear-cutting of loblolly pine stands in eastern Texas. Site preparation included the cutting of hardwood stems greater than one inch (2.5 cm) in diameter at breast height. Slash burning had no effect on soil bulk densities, which averaged 1.29 Mg/cm^3 . Cutting with a Marden chopper and burning increased the mean soil bulk density to 1.33 Mg/m^3 ; and cutting with a KG blade, raking, and burning increased the mean to 1.40 Mg/m^3 .

In the past, several inches of soil has been pushed from some areas into windrows with brush. This practice has generally been abandoned following observations of poor tree growth in the severely scalped areas. Now brush rakes which minimize the displacement of soil are used to move brush and pile it. Still, two inches (5 cm) of soil is commonly removed from some areas in California during site preparation with tractors.

Small tractors cause less compaction than large tractors. Nevertheless, large tractors are often used for site preparation, because they are more readily available from timber harvesting, or because it is desired to remove large stumps.

Two site preparation practices which have marked effects on soils are terracing in steeper terrain and bedding in flatter terrain. Bedding is the amassing of soil and organic debris into ridges 15 to 20 cm high and 1 to 2 m wide. (Haines et al., 1975). It is most commonly practiced in the more poorly drained soils of the Atlantic Coastal Plain. Bedding was effective in increasing the growth of loblolly pine seedlings where disking of compacted, poorly drained soils was not effective in a clearcut of the Santee Experimental Forest, South Carolina (Hatchell, 1981).

3. Range management.

Cattle and horses apply more stress (force/area) to soils than most tractors (Lull, 1959). However, due to less weight, they do not compact soils as deeply as tractors. Alderfer and Robinson (1947) found in one study of pastures in Pennsylvania that compaction by livestock was mostly limited to the uppermost inch (2.5 cm) of soil. They found in a more extensive study (Robinson and Alderfer, 1952), however, that most of the compaction in 32 permanent pastures was in the 1 to 5 inch (2.5 to 12.5 cm) depth range and the structure of the more compacted soil was platy. Johnson (1952) found in North Carolina that the total soil porosity in woodlands was reduced most (56%) in the 2 to 4 inch (5 to 10 cm) depth range by heavy grazing but that lighter grazing reduced the total soil porosity more in the 0 to 2 inch (0 to 5 cm) than in the 2 to 4 inch (5 to 10 cm) depth range. Fifteen years of grazing a tall grass prairie in central Missouri increased the bulk density in the uppermost 4 inches (10 cm) of soil,

but no deeper (Kucera, 1958). Keen and Cashen (1932) found that sheep compacted sandy soil to 10 cm depth, with the greatest compaction, based on soil strength, at the 3 to 4 cm depth. Edmond (1958) found that the bulk density of a Manawata silt loam increased with stocking density of sheep from 1.08 to 1.16 Mg/m³ at 0 to 1.5 cm, from 1.17 to 1.26 Mg/m³ at 1.5 to 3.0 cm, and from 1.20 to 1.28 Mg/m³ at 4.5 to 6 cm depth. Chandler (1940) found a mean bulk density of 1.15 Mg/m³ in heavily grazed second growth hardwood stands of central New York compared to 0.92 Mg/m³ in ungrazed stands, not grazed by cattle. This is much less a difference than Alderfer and Robinson (1947) found between heavily and lightly grazed pastures in Pennsylvania. Auten (1933) found, that grazing increased the bulk density in the surface 23 cm of soils in Ohio woodlands by 15%. McCarty and Mazurak (1976) found surface bulk density increases from 1.02 Mg/m³ in ungrazed plots to 1.14 Mg/m³ in deferred and rotationally grazed plots to 1.22 Mg/m³ in continuously grazed plots in eastern Nebraska.

Surface soil compaction affects the macropores more than it affects bulk density and total porosity. Read (1957) sampled the surface 3 inches (7.5 cm) of A horizons in both protected and heavily utilized parts of 3 shelterbelts in South Dakota. The relative increase in mean bulk density with utilization by livestock was 21%, from 1.01 to 1.22 Mg/m³. However, the relative decrease in mean macropore space (pores >0.02 mm) was 46%, from 14.1 to 7.6%.

Sant (1966) found in India that heavy grazing had little effect on the surface soil capillary porosity but decreased the macroporosity as much as 52% depending of the season of useage.

Steinbrenner (1951) investigated 6 pairs of grazed and adjacent ungrazed farm woodlots in southern Wisconsin. The grazed and ungrazed woodlots in each pair had the same soils and slope gradients and aspects. Steinbrenner found an absolute decrease in surface soil macropore (pores >0.66 mm) space mean of -9.9%, from 26.1 to 16.2%, in ungrazed to grazed woodlots, but an absolute increase in micropore (pores <0.66 mm) space mean of 4.8%, from 41.3 to 46.1%, in ungrazed woodlots. The decreases in rates of transmission of air and water from soils in ungrazed to those in grazed woodlots was even more pronounced than the decrease in macropore space.

Brown and Schuster (1969) found that grazing on the Llano Estacado of Texas increased soil strength much more than bulk density. Soil bulk density in a grazed area was 18% greater in the surface 10 cm and 13% greater at 15 to 25 cm depth than in an ungrazed area, but the penetrometer resistance was 6 times greater.

Concern about the impacts of grazing in the western United States has been focused on infiltration, runoff, and soil erosion more than on soil compaction. Infiltration is affected by grazing in ways other than through soil compaction and reduction of soil macroporosity. Grazing and trampling alter the vegetation and litter covering the soil. Then reduced interception of rainfall by plants and ground surface litter and soil crusting reduce infiltration rates. Gifford and Hawkins (1978) have reviewed the literature about grazing impacts on infiltration of water into soils. Liacos (1962) found that grazing decreased infiltration and greatly increased the runoff from annual grassland in California. Meeuwig (1965) found infiltration to be more closely related to macroporosity in the surface 5 cm of soil than to surface cover.

4. Recreation.

Soils in arid areas are impacted directly by ORVs and foot traffic. However, in humid areas soils are protected by vegetation and its litter covering the ground surface. This cover of organic litter must be dissipated or displaced before there will be much impact on the soil. Once the soil is exposed by loss of the organic litter cover, it is much more susceptible to displacement and compaction. The structure of exposed soil may deteriorate even without further human impact (Lunt, 1937). Soil displacement and compaction by recreational activities sets the stage for further degradation by the erosive stresses of wind, rainfall, and gravity. Soil compaction increases runoff and soil displacement, causing concentrations of water that make the erosive forces more effective.

a. Foot traffic and campgrounds. The effects of foot traffic are negligible when soils are covered with organic litter. Therefore, the impacts of foot traffic on soils are generally confined to picnic sites, trails, and campgrounds where traffic is concentrated in limited areas. Vehicles contribute

to soil disturbance and compaction in some campgrounds, and riding and pack animals contribute to soil disturbance on some trails. Magill (1970) has recommended barriers to restrict vehicle traffic in campgrounds. This reduces campground deterioration.

In 3 soils of 2 picnic areas in Connecticut, Lutz (1945) found much greater bulk densities in used areas than in unused areas. Bulk density differences in the surface 4 inches (10 cm), from used to unused areas on the 3 soils, were 0.91 to 1.06, 1.06 to 1.30, and 1.01 to 1.37 Mg/m³. These are increases of 16, 23, and 36%. Compaction in the next 4 inches (10 to 20 cm depth) was less but still substantial.

Other investigators found comparable surface soil bulk density increases in campgrounds of Colorado (Dotzenko et al., 1967, 46% average increase), Missouri (Settergren and Cole, 1970, 21 to 28% increase), Michigan (Legg and Schneider, 1977, 34% average increase), Iowa (Dawson et al., 1978, 30% average increase), Ontario (Montl and Mackintosh, 1979, 34% average increase), and Oregon (Cole and Fichtler, 1983, 8% increase). Crawford and Liddle (1977) found an increase in mean bulk densities of 39%, up to 0.93 in heavily trampled areas near the bank of the River Thames from 0.67 Mg/m³ in lightly trampled areas some distance from the bank. Merriam and Smith (1974) found in northern Minnesota that most of the user impact and compaction occurred during the first two years a site was occupied by campers. Liddle and Greig-Smith (1975) have suggested that the increases in bulk density and soil strength are logarithmic, a suggestion supported by their data for both vehicle and pedestrian traffic.

Several investigators have used penetrometers as indicators of compaction in campgrounds. They found increases in surface soil strength in New Hampshire (LaPage, 1962), in Michigan (Ward and Berg, 1973), in Illinois (Young and Gilmore, 1976), in Iowa (Dawson et al., 1979), in Ontario (James et al., 1979), and in Montana (Cole and Fichtler, 1983). Montl and Mackintosh found in Ontario that infiltration rates in campgrounds were reduced by factors of 20 to 30 times.

Settergren and Cole (1970) found in Missouri campgrounds that an average of 3 inches (7.5 cm) of surface soil was lost from used areas by compaction, displacement, and erosion. They found that roots were concentrated in the upper 6 inches (15 cm) of soil in unused areas but were sparse in the upper 6 inches (15 cm) of used area soils.

Liddle and Greig-Smith (1975) compared the compaction of vehicle and pedestrian traffic. The ground pressures were 1.8 kg/cm^2 for pedestrians, 9.5 kg/cm^2 in car tracks on soft ground, and 15 kg/cm^2 in car tracks on hard ground. The mean surface soil bulk densities were 1.10 Mg/m^3 in undisturbed areas, 1.27 Mg/m^3 in foot paths and picnic areas, and 1.34 Mg/m^3 in car tracks. Chappell et al. (1971), also in England, stratified a country park into areas of (1) minimal use and grazing by sheep, (2) trampling but no visible soil disturbance, and (3) trampling and vehicle rutting. They found mean soil bulk densities in the 3 areas of 0.681, 0.827, and 1.018 Mg/m^3 at the 0 to 2.5 cm depth and 0.958, 1.020, and 0.996 Mg/m^3 at the 2.5 to 5 cm depth. Compaction was almost entirely limited to the uppermost inch (2.5 cm) of soil. Bates (1935) suggested earlier in England that puddling and crust formation have more effect on the vegetation of soils walked upon when wet than does soil compaction.

Weaver and Dale (1978) compared the trampling effects of hikers, horses, and motorcycles on level ground and 15% slopes in Idaho fescue meadow with deep nonstony sandy loams and in white-bark pine (*P. albicaulis*)/huckleberry (*V. scoparium*) stands with deep stony sandy loams. Trail width, depth, and bare ground all increased (logarithmically by my interpretation of the graphs) up to practically 1000 passes, except that bare ground reached a maximum at less than 500 passes with horse and motorcycle traffic. Trail depths were greater in the nonstony soil and were increasingly deep for hikers, motorcycles, and horses. Soil compaction increased in the same order - hiker < motorcycle < horse traffic - and was greater on 15% slopes than on level ground. Upslope and downslope traffic effects were compared in the meadow. Soil disturbance was greater for hikers and horses when traveling downslope and for motorcycles when traveling upslope. Trail width was greater for downslope travel of hikers and for upslope travel of horses.

In addition to the more immediate compaction by vehicle traffic and trampling, the bulk densities of soils in campgrounds may increase due to gradual losses of organic matter. Willard (1971), for example, has reported soil organic matter losses. Several investigators have reported reductions in tree diameter growth rates in campgrounds. Slatter (1978) found a highly significant negative correlation between surface soil bulk density and the maximum height of vegetation along paths. In Michigan campgrounds, Legg and Schneider (1977) discovered partial recovery of surface soil porosity (reduction of bulk density) over a winter. The soils in the Mountain Oak and Mescal Campgrounds of the Angeles National Forest were so disturbed and compacted after 30 years of vehicle and foot traffic that plants could no longer be reestablished in them. Hence, these two campgrounds were closed in 1967 for rehabilitation.

Liddle (1975) has reviewed the effects of trampling on the vegetative cover of campgrounds and trails. The Intermountain Forest and Range Experiment Station of the Forest Service has published two annotated bibliographies covering the impacts of recreation: Stanley and Lime (1973) and Cole et al. (1981).

b. Off-road vehicles. Off-road vehicle traffic is generally more of an environmental problem in arid areas than in humid areas. In humid areas that are uncultivated, trees or other dense vegetation limits the mobility of vehicles such that off-road vehicle traffic is confined to relatively small areas. However, the effects on soils in the smaller areas can be more extreme. The lasting effects of landscape alteration during the Barstow to Las Vegas motorcycle race on public land made many citizens aware of the potential for environmental damage by off-road vehicles in arid regions. A picture taken of motorcyclists lined up to begin the Barstow to Las Vegas race appears on the cover of a recent book about off-road vehicle impacts (Webb and Wilshire, 1982).