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Title: SOIL AND UNDERSTORY VEGETATION CHARACTERISTICS OF A TRACTOR-LOGGED FOREST IN EASTERN OREGON

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A 1.5 ha mixed conifer stand in the Blue Mountains of Oregon was intensively examined to assess the impact of logging disturbance on soils and herbaceous vegetation. Sampling was conducted six years after much of the timber overstory was removed in a shelterwood cut and yarded by crawler tractor. A year after harvest slash was machine-piled and burned. Skid trails and other areas of disturbance were seeded with a mixture of perennial grasses.

Logging impact was divided into five "disturbance classes" as treatments: general, berm, slash fire ring, skid trail, and undisturbed. Analysis of variance was used to test treatment differences. Characteristics of skid trails were analyzed separately from those of non-skid trail areas.

Soil compaction was evident on skid trails from substantially lower rates of infiltration and saturated hydraulic conductivity (SHC), and a higher average soil strength, relative to undisturbed areas. Skid trail compaction probably resulted from mixing of

denser subsoils with the low-density volcanic ash soils at the surface, and from compression by tractor activity. Bulk density of skid trails was not statistically different from that of undisturbed areas. Soil densities of all classes of disturbance were generally lower than 0.9 g/cm^3. Non-skid trail areas were not compacted.

Soil water conductance rates markedly differed among disturbance classes, but were considerably higher than storm intensities projected for the region. High sample variability of both infiltration and SHC rates made interpreation of statistical comparisons among treatments difficult.

Some watershed protection values were diminished on the disturbed areas. Litter cover of skid trails, general disturbance areas, and berms was 27, 45, and 68 percent lower, respectively, than that of undisturbed areas. Depth of litter decreased correspondingly among the disturbed treatments. Litter was nearly absent on the fire rings. Another agent in soil stabilization, belowground biomass, was two-thirds less on skid trails, in comparision with undisturbed areas.

Amounts of soil organic matter in the surface 3 cm were significantly lower for the four types of ground disturbance, relative to undisturbed areas; however, organic matter was higher at some subsurface levels of berms, fire rings, and skid trails. Bulk density of non-skid trail soils was inversely correlated with organic matter content.

There were no statistically significant differences among treatments for soil water retained at four potentials, for coarse mineral fragment content, or for fine earth particle size distribution.

Aboveground vegetation production of the seeded skid trails was 66 percent greater than that of undisturbed areas. Understory plant cover of skid trails and undisturbed areas was equivalent. Correlation between aboveground herbaceous production and soil strength at the 5-10 cm depth of skid trails was not statistically significant.

Soil and Understory Vegetation Characteristics of a Tractor-Logged Forest in Eastern Oregon

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INTRODUCTION

Logging by tractor is the most common method of harvesting timber on gentler terrain in eastern Oregon and Washington, as in much of North America today (Froehlich 1973). Compared with other harvest methods, tractor logging is often advantageous economically and practically; however, ground disturbance resulting from tractor logging is frequently more severe than disturbance caused by alternative harvest methods (Steinbrenner and Gessel 1955, Satterlund 1972). It is not unusual for 25 percent or more of a tractor-logged area to be consigned to skid trails, and for more than half of the site to receive some form of surface disturbance Dyrness 1965; Froehlich 1973).

A key component of Eastside forests is the understory vegetation, which provides forage for large numbers of grazing animals, both wild and domestic. In addition, the forest understory holds topsoil in place. The volcanic ash soils that blanket much of the Eastside forested region easily erode when the protective cover of vegetation and plant litter is removed during logging activity (Geist and Strickler 1978). Erosion can permanently lower soil fertility of logging areas (Moehring 1970).

Productivity of a forest can also be diminished by the compaction, displacement, and puddling of soils that often accompany tractor logging (Moehring 1970). Sediment-laden runoff from eroding logging areas may degrade quality of streams and catchments (Brown 1979)-- important in the interior Pacific Northwest for a diversity of fishery, irrigation, recreation, hydro-power, and community needs. Several studies in forests west of the Cascade Mountains have found reduced tree growth and increased erosion potential on areas logged by tractors (Steinbrenner and Gessel 1956, Youngberg 1959, Johnson and Beschta 1980, Wert and Thomas 1981). Comparable research in Eastside forests has been scarce.

In the relatively xeric environment of the interior Northwest, forest soils bared of vegetation by logging often remain denuded for extended periods or, alternatively, are invaded by low-value, early-drying (i.e. fire hazardous) annual grasses and forbs (USDA Forest Service 1957, Hedrick et al. 1968). Therefore, artificial seeding of logged areas with a mixture of perennial grasses has become standard practice in the region. On many logged sites artificial seeding offers the double advantage of curbing erosion and maintaining or increasing pre-logging amounts of forage.

This study was conducted to assess the effect of tractor logging on soil properties and herbaceous growth of an Eastside forest stand 6 years after timber harvest. The stand was a mixed conifer, ash soil community type (Hall 1973), which is one of the most common forested plant communities in Oregon's Blue Mountains and is important commercially for its timber and grazing values (Hall 1973, 1980). Following slash clean-up by piling and burning, tractor skid trails were seeded with several introduced grasses.

The study objectives were:

1) Compare production of above- and belowground biomass between seeded skid trails and undisturbed areas on the site.

2) Determine degree of soil compaction by the indices of bulk density, infiltration, saturated hydraulic conductivity, and penetrometer resistance.

3) Evaluate the effect of logging disturbance on factors related to plant growth and watershed quality. These factors include vegetation cover, litter cover and depth, and the soil parameters of organic matter content, moisture retention, particle size distribution, infiltration, saturated hydraulic conductivity, bulk density, and strength.

This thesis is arranged in "manuscript" format. A review of literature is followed by the research report, separated into two sections. Each section is written in the form of a manuscript for publication in the Soil Science Society of America Journal.

LITERATURE REVIEW

The Eastside Pine Forests of Oregon and Washington: Their Grazing and Timber Values

Forests dominated by ponderosa pine (Pinus ponderosa) and associated species are extensive in eastern Oregon and Washington, covering about 8.1 million hectares (Denham 1960). The pine climax community is commonly open and savanna-like, with a mosaic of grasses and herbs in the understory (Moir 1966). In the more xeric areas ponderosa pine is the sole overstory constituent above an understory composed of bunchgrasses, primarily Idaho fescue (Festuca idahoensis), bluebunch wheatgrass (Agropyron spicatum), and squirreltail (Sitanion hystrix) (Hall 1973). As elevation and precipitation increase, ponderosa pine shares dominance with several other conifer species, including Douglas-fir (Pseudotsuga menziesii), grand fir (Abies grandis), and larch (Larex occidentalis). The overstory of a mixed conifer forest sometimes includes a dense mid-layer of shade tolerant firs beneath the pine canopy (Hall 1973). Pinegrass (Calamagrostis rubescens), elk sedge (Carex geyeri), and the forb heartleaf arnica (Arnica cordifolia) typically comprise the understory of the mixed conifer forest, often to the near exclusion of other species.

Presence of shrubs throughout the eastside pine forests is sporadic. In the northern Blue Mountains ninebark (Physocarpus malvaceus), oceanspray (Holodiscus discolor), and spirea (Spirea betulifolia) are common important understory components, but these shrubs become less frequent and nearly disappear in the southern reaches of the same mountains (Hall 1973).

Livestock grazing in the pine forests of the interior Pacific Northwest is less than a century old (Skovlin and Harris 1974). Hall (1980) has suggested natural frequent underburning in the mixed conifer forests has evolved an herbaceous understory capable of withstanding severe defoliation; hence, these forests make suitable grazing land for domestic animals as well as wildlife. Pine-bunchgrass forests in the region furnish summer grazing for 250,000 beef (Bos taurus) and nearly as many sheep (Ovis aries). The Blue Mountains alone support approximately 200,000 deer (Odocoileus hemionus hemionus) and 75,000 Rocky Mountain elk (Cervus elaphus nelsoni) (Skovlin et al. 1976).

Forested summer range is at a premium in the region. Only half enough summer forage is available for the number of livestock that can be produced on spring-fall range (Skovlin and Harris 1970). This imbalance exists in part from past overgrazing abuse (Skovlin et al. 1976). However, fire suppression has also taken its toll on available forage. Hall (1980) pointed out that between 1940 and 1970, forage production in Blue Mountain forests was reduced 16 percent as a result of forest canopy closure due to suppression of natural understory burning.

Each year between 2 and 4 percent of Eastside pine lands are logged, resulting in the immediate destruction of one-quarter to one-third of the herbaceous and shrub cover on these sites (Denham 1960, Garrison 1961). Yield, composition, distribution, and quality of understory forage may be radically altered as a result of timber harvesting. Logging may also have a profound effect on animal movement and distribution. Edgerton (1973) noted timber harvesting is the greatest single influence on wildlife habitat in the Northwest. Logging is not necessarily detrimental to wildlife populations. Elk, for instance, are known to often prefer clearcut areas (Edgerton 1973, Miller 1974). As a rule, if logging opens the stand sufficiently, the effect of timber harvesting over the long run is to increase amount and quality of forage (Reid 1965).

Timber will probably remain a dominant economic product of Eastside forests. The region produces one-third of the national output of ponderosa pine timber, which is generally of higher quality than that of other pine-producing areas (Gedney 1963, Skovlin et al. 1976). Yet, sometimes overlooked is the economic return from animals grazing on these timbered lands. Wood (1972) noted grazing revenues from ponderosa pine forests are often equivalent to timber values when compared on an annual income basis. McConnell and Smith (1965, 1970) suggested programs for thinning ponderosa pine take into account the parallel benefits of increasing forage yields; thinning specifically for forage production might be justified on selected key areas, such as big game winter ranges where forage is in acute short supply.

The Relationship Between Understory Vegetation and Trees

Effect of Trees on Understory Vegetation

"Forage production on forested rangelands," stated Krueger (1980:5), "is principally controlled by the trees making up the overstory." Many researchers have assumed the response of understory vegetation to canopy cover is primarily a function of light intensity (Anderson et al. 1969). However, many variables have been identified as possible governing factors in the tree canopy/understory-relationship, including moisture loss from canopy interception, competition in the root zone for moisture and nutrients, and allelopathic substances produced by the trees (Moir 1966, Jameson 1967, Anderson et al. 1969).

In eastern Oregon, competition for moisture is probably the dominant factor governing total yield of vegetation under typical forested range canopies. However, during seasons when moisture is abundant, light and temperature may be controlling agents (Krueger 1980). In foothill conifer communities of northeastern Oregon, Miller and Krueger (1976) found canopy cover and soil depth accounted for 96 percent of the variability in understory production. In eastern Washington, Moir (1966) found ponderosa pine clusters past the seedling stage began to compete for light and soil nitrogen; hence, herbaceous growth was suppressed early in pine development. It was speculated that, barring thinning, trees would eventually reduce both light and nitrogen available to the forest floor, to the eventual near-total exclusion of the understory.

The effect of canopy closure and release on understory growth can be striking. In a Missouri oak forest, Martin et al. (1955) found forage production in openings was as much as 40 times that of dense timber stands. Cooper (1960) found the predominantly grassy understory of a pine forest in Arizona declined 24 kg/ha with each 1 percent increase in pine crown cover; little or no grass was present in areas with more than 75 percent canopy cover. McConnell and Smith (1970) reported a strong linear relationship ($r^2 = 0.97$) between total understory herbage yield and tree coverage on a thinned ponderosa pine site in eastern Washington. Eight years after thinning there was a 7 kg/ha increase in understory yield for each 1 percent decrease in tree canopy. This was triple the rate determined 3 years following thinning on the same stand (McConnell and Smith 1965). Where pine canopy exceeded 45 percent, forbs outproduced grasses; below 45 percent coverage, grasses prevailed. In a longleaf pine (Pinus palustris) forest, Gaines et al. (1954) found tree distribution pattern affected growth of understory. A single tree with an 18-36 cm dbh influenced grass production 1.8 to 2.4 m from the trunk, whereas a group of trees affected production 6-9 m from the forest wall.

Browse, an important constituent of big game diets, is also affected by change in the forest crown cover. McConnell and Smith (1970) found shrubs, primarily bitterbrush, increased about 7 kg/ha for each 1 m increase in pine spacing, and 1.1 kg/ha for each 1 percent decrease in tree canopy. In a mixed conifer forest in northeastern Oregon, Young et al. (1967) found a positive curvilinear relationship between shrubs and tree canopy. Shrub production in areas of moderate shade was 14,000 kg/ha--approximately double that of open or heavily shaded areas.

Forage quality can change with canopy coverage. Hedrick et al. (1968) determined crude protein levels of herbage in areas opened by logging was higher than on unlogged areas. Wood (1972) reported unshaded plants tend to produce more sugars than plants growing beneath a forest canopy. This difference may be a function of light quality as well as intensity (Krueger 1980). Early in the growing season, plants in the open may contain higher amounts of digestible energy and perhaps phosphorus, but are probably similar in protein levels, compared with shaded plants. On the other hand, late in the season the nutrient quality of shaded plants will be superior to those growing in the open that mature earlier. At this time, shaded plants will be higher in protein, digestible energy, and probably phosphorus, and will be more nutritious to the grazing animal (Krueger 1980).

Litter, a by-product of the tree overstory, often diminishes understory growth. Gaines et al. (1954) found herbaceous production rapidly decreased as tree litter increased in a longleaf pine forest. McConnell and Smith (1971) noted pine litter appeared to smother plants, particularly grass seedlings.

Effect of Understory Vegetation on Tree Growth

To what extent competition from the forest understory influences establishment, survival and growth of desirable trees is an enduring controversy. With some exceptions, studies have determined understory species compete directly with trees for moisture, nutrients, and light. From the standpoint of the growing trees, competition from the understory is probably strongest at the tree seedling stage. Sowder (1960), however, pointed out competition of trees with other trees can be more than three times as severe as competition with grasses, brush, and other ground vegetation. Barrett and Youngberg (1965) reported cover of understory vegetation was closely correlated with reduced tree growth and increased water use on a sapling ponderosa pine stand. In California, Roy (1953) found poor survival of ponderosa pine and Jeffrey pine (*Pinus jeffreyi*) planting stock under light and heavy cover of grasses, sedges, and shrubs. Differences in tree survival were thought to be associated with moisture differences. It was recommended that patches of vegetation be avoided when planting pine. Gjertson (1949) found no evidence seeded forage species decreased subsequent ponderosa pine regeneration on 52 sites in the Pacific Northwest. Stewart and Beebe (1974) found pine survival in areas seeded to grasses was highly influenced by soil type. Survival of trees in pumice soil was 39 percent, whereas, on residual soil only 3 percent survived.

Sowder (1960) indicated trees planted at the same time as seeded forage species have a good chance of survival; apparently, it is the older, well-established understory that hinders tree seedling growth. Hall (1980) noted 80 percent of trees planted on seeded clearcuts in eastern Oregon and Washington will survive if they start their first growing season at the same time grass is germinating, but, for each year's delay in planting trees after grass establishment, there will be a 30 percent decrease in tree survival. Denham (1960) recommended seeding logged areas in the fall and planting trees the following spring to gain a satisfactory stand of both grasses and trees. Sassaman (1972) noted planted forages grow in place of low-value species that often invade following logging; therefore, artificially seeded herbaceous cover does not increase competition with trees for available moisture. The practice of seeding short-lived forage species on denuded logged areas may benefit conifer reproduction by breaking up soil compacted during timber harvest (Young et al. 1967).

In many eastern Oregon and Washington pine forests, the major problem is not how to achieve more tree reproduction, but what to do with stands presently overstocked with stagnating pine, and how to prevent further "dog-hair" stands from regenerating (Denham 1960, Hall 1980). In this context understory competition may aid the forester by helping eliminate natural overstocking (Denham 1960).

The Influence of Timber Harvesting on Understory Vegetation

Effect of Logging on Understory Vegetation

Logging, along with build-up and disposal of slash residue, can profoundly alter the forest floor environment which, in turn, will affect growth of understory species. Forest canopy reduction typically changes ground surface temperatures, as well as humidity, air flow, and precipitation distribution on the logged sites; intensity and quality of light shift; and competitive relationships for moisture and nutrients in the rooting zone change. Passage of mechanized equipment and logs over the forest floor often removes large amounts of understory vegetation and promotes long-term changes in soil physical, chemical, and biotic properties. The effect of these disruptions on production and composition of the forest understory may persist for many years.

Surveys reported by Gjertson (1949) on logged areas in the interior Pacific Northwest revealed 10 percent or more of the ground was completely denuded of vegetation during timber harvests. These bare areas consisted of skid trails and roads, landings, and places where slash had been burned. In northeastern California, Hormay (1940) found 14 percent of a tractor-logged pine stand cleared of vegetation, litter, and logging debris. Desirable perennial forage species were most susceptible to tractor logging. Garrison and Rummell (1951) reported tractor logging immediately reduced herbaceous and shrub cover by 47 percent on several sites in eastern Oregon and Washington. Because of their shallow root and rhizome systems, grasses and sedges were most susceptible to destruction. Arnold (1953) recommended against heavy selection logging in a northern Arizona pine forest, since increased production from canopy release was more than cancelled by loss of the better perennial bunchgrasses from surface soil disturbance and presence of slash.

Changes in understory characteristics brought about by tractor logging were reported by Young (1965), Young et al. (1967), and Hedrick et al. (1968) for a mixed coniferous stand in northeastern Oregon. Sanitation logging produced both beneficial and deleterious effects on herbage and shrub growth. Where old openings in the canopy were enlarged or new ones created, herbage production greatly increased; but other areas were taken out of production by heavy soil disturbance and slash accumulation. Pinegrass (Calamagrostis rubescens), a major forage species, appeared to respond favorably to moderate amounts of soil disturbance. However, areas of heavy soil disturbance produced only one-third as much herbage as undisturbed areas three years after logging.

In pine forests of the interior Pacific Northwest, full recovery of pre-logged understory composition, production, and cover may take a decade or longer. Generally, recovery is quicker on areas lightly disturbed from logging than on areas of heavy ground disturbance. In northeastern Oregon, Edgerton (1973) found total plant cover on two partially cut mixed conifer sites was still less than that of uncut areas 5 years following logging. For a pine forest in eastern Oregon, Hall (1980) reported indigenous pinegrass and elk sedge (Carex geyeri) required 10 years to fully re-occupy the ground after the canopy was thinned from 98 percent to 21 percent coverage. Basile and Jensen (1971) found total understory production following clearcutting of a lodgepole pine (Pinus contorta) forest in Montana reached its peak 11 years after harvest; maximum yield was achieved chiefly by shrubs and forbs. Clearcutting lodgepole was estimated to open the forest to grazing for at least 20 years.

Plant succession following logging of several pine stands in the interior Pacific Northwest has been described in a series of reports by Garrison and Rummell (1951), USDA Forest Service (1957), Garrison (1961), and Garrison (1965). Following initial heavy depletion of ground cover on the pine-pinegrass-elksedge type, forb growth was vigorous, reaching a peak cover, in the 4th year after logging, two-thirds greater than the pre-logging percentage. By the 4th year grasses and shrubs were respectively 22 and 14 percent below pre-logging amounts. By the 7th year grasses were practically restored to their original cover, shrubs had attained about 89 percent of their original cover, and forbs continued to be abundant. Recovery of severely disturbed skid trails lagged markedly behind less disturbed areas. In the 7th year following logging, skid trails had reached an estimated successional status equivalent to only 2 years for the less disturbed areas. On a more xeric pine-bunchgrass (*Pinus ponderosa*-*Agropyron inerme*-*A. spicatum*) site, succession followed a somewhat different course. By the 7th year after logging, low-value cheatgrass (*Bromus tectorum*) had invaded the stand, and total vegetation cover was 16 percent less than pre-logging coverage. Garrison (1965) noted most selectively logged areas will approach full revegetation with desirable forage species by the 14th year after logging; however, recovery of skidding scars may be incomplete, and pine seedling establishment will be sporadic on areas denuded by logging.

Effect of Slash on Understory Vegetation

Logging slash affects understory vegetation by altering the forest floor microclimate and by physically blocking plant growth (Garrison and Smith 1974). Slash has been variously regarded as a potential fire hazard, habitat for tree-damaging rodents and insects, and a potential resource (Roy 1953, Young et al. 1967, Aulerich et al. 1974).

Accumulation of logging slash can be substantial. Garrison and Smith (1974) cited studies by Hall (1967) and Sundahl (1966), which showed logging slash on selectively cut pine forests in the interior Pacific Northwest may total 27 to 90 metric tons/ha; in patch cut areas slash may total 112 to 246 tons/ha, with 60 percent of this weight in material less than 10 cm in diameter. Dyrness (1965) reported slash covered about 74 percent of a clearcut stand in western Oregon. Hormay (1940) found slash on 24 percent of a tractor-logged pine stand in northeastern California. In northeastern Oregon, Hedrick et al. (1968) determined 17 percent of a mixed coniferous forest logged by tractor was occupied by slash and woody debris, compared with 4 percent for an unlogged stand.

Slash has been implicated for major losses of forage production following logging. In a ponderosa pine forest in northern Arizona, Arnold (1953) found tree overstory reduction combined with slash cleanup produced greatest increases in herbaceous vegetation. Greatest losses in herbaceous vegetation occurred on areas where slash accumulation was heavy, as well as on areas where tree canopy increased. However, in the same region, Reynolds (1966) found slash cleanup had no measurable effect on total production and composition of understory. Garrison and Rummell (1951) found piling and burning slash was more detrimental to understory vegetation than the practice of lopping and scattering slash.

Deer and other wildlife may find temporary escape cover in slash; however, movement of grazing animals, both wild and domestic, may be hindered by large amounts of logging residue (Garrison and Smith 1974). Hall (1980) reported forage yield increased on a heavily thinned stagnated pine stand, but the cut trees left lying on the ground created an impenetrable obstacle to livestock. Reynolds (1966) observed cattle preferred slash-free areas; on the other hand, deer, possibly feeling conspicuous in slash-free areas, tended to be more abundant where slash was not cleared. Slash may cause livestock to concentrate on smaller areas after logging, thus promoting overgrazing and invasion of weedy species (Weidman 1936, Wood 1972). Cattle movement may be facilitated by positioning unremoved logs parallel to the hill slope (Hedrick et al. 1968, Wood 1972). Inhibition of animal movement by slash will decrease with time as the material decays (Garrison and Smith 1974).

Soil Disturbance From Tractor Logging

Introduction: Types of Disturbance

Soil is viewed by the wildland manager as a medium for plant growth, as a watershed storage reservoir, and as a potential source of unwanted sediment in watershed runoff. The manager strives to maintain the soil at, or near, optimum conditions to supply plants with needed water, nutrients, oxygen, and growing room. A simultaneous goal is maintenance of long-term soil stability.

Timber harvesting, along with slash treatment and silvicultural practices, are major causes of forest soil disruption. These disturbances can potentially lower the soil's effectiveness as a plant growth medium and can damage site stability. Tractor logging-- by rubber-tired skidder or crawler tractor-- can generate extensive soil disturbance because tractors require a dense network of trails throughout the entire harvest area (Steinbrenner and Gessel 1955). Garrison and Rummell (1951:709-710) furnished a vivid picture of ground disturbance from tractor logging:

> The major ground disturbance on tractor-logged areas resulted from ground skidding of logs, construction of spur roads, and construction and use of landings. In the process of skidding logs from stump to landing, the moving logs being pulled by the tractor tore out vegetation, displaced litter, and dug into the soil along their path... Where ground skidding was practiced, the forward ends of the logs seriously plowed the soil. This became even more serious when the logs were allowed to trail far behind the tractor. With repeated use, the denuded skid trails were deepened, soil compacted..., and the excavated material moved out to form berms along the sides of the trails. The scraping and clawing actions of the tractor treads hastened the development of skid trails and denuded additional portions of the forest floor.

Types of soil disturbance usually associated with tractor logging are compaction, puddling, and soil displacement. Of these, compaction-- i.e., soil densification-- has received by far the most research attention, perhaps because compaction is a widespread problem, having the potential to damage plant growth for many years over considerable portions of a logged site.

Puddling occurs when large soil pores are filled with smaller particles, and when clay particles are oriented so that they lie parallel to each other (Kohke 1968, Moehring 1970). Puddling results from excessive kneading action at the soil surface as well as from raindrop impact (Satterlund 1972, Hillel 1980). The resulting massive, non-structural soil condition restricts seedling radicle and plant root growth, and hinders air and water movement to plants (Pomeroy 1949, Hatchell et al. 1970). Gases toxic to plants build up in puddled soils in the presence of high amounts of organic matter and anaerobic conditions (Steinbrenner 1966). Recovery time for puddled soils may be less than that for compacted soils because the puddled crust is typically less thick than compacted soils (Moehring 1970).

Soil displacement, as described by Moehring (1970:329) is the "churning, rutting, scalping, and erosion of soil by mechanized equipment used in logging and site preparation." Displacement can involve horizontal movement of soil on the site (Boyer 1979). Soil displacement usually represents a permanent reduction in a site's nutrient potential, and natural recovery is generally very slow (Moehring 1970).

Other kinds of soil disturbance resulting from logging activity include disruption of surface drainage characteristics (Moehring 1970), and mass movement, usually associated with construction of logging access roads (Satterlund 1972).

Erosion

Erosion is a by-product of the various forms of soil disturbance. Soils bared of vegetation and litter cover during tractor logging are vulnerable to rainsplash (Satterlund 1972), and churned or displaced soil is usually subject to erosion

(Moehring 1970). Erosion is induced by overland water runoff, which occurs when a soil's capacity to absorb moisture is exceeded by the rate precipitation reaches it (Branson et al. 1981). Compaction from mechanized equipment can be a major contributing factor to erosion on a logged site, since compaction typically lowers a soil's infiltration rate. As areas of concentrated traffic, skid trails are particularly prone to soil disturbance and consequent erosion. Skid trails tend to channel surface runoff (Garrison and Rummell 1951, Dyrness 1965), and intercept and concentrate water moving downhill through the soil mantle (Steinbrenner 1966).

Jenny (1980:296) has stated, "Forests are a renewable resource, but the silvicultural aim of sustained yield is negated unless the soil is preserved." Logging-induced erosion can lower a forest's long-term productivity by removing essential nutrients. Sedimentation of downstream channels and catchments is an additional harmful result of accelerated forest erosion (Satterlund 1972). Overland flow caused by reduced infiltration capacities on logged sites may contribute to increased peak flows from a watershed (Satterlund 1972).

On several tractor-logged watersheds in western Oregon, Johnson and Beschta (1980) found skid trails to be sites of lowered infiltration rates and higher erodibility than watershed averages. The highly disturbed trails were generally areas with least vegetation cover and most soil exposure, where dislodged silt and clay particles could readily seal surface macropores.

In perhaps the only published study on the subject in the interior Pacific Northwest, Helvey and Fowler (1979) found evidence of erosion on heavily disturbed skid trails on a clearcut in northeastern Oregon, but found no evidence of erosion on less disturbed soils. Soils on the site were of volcanic ash origin.

Extent of Soil Disturbance on Tractor-Logged Sites

Soil disturbance from tractor logging can be extensive. Tractor trails commonly occupy 25 percent or more of a harvested site (Froehlich 1979). In the Douglas-fir region of the Pacific Northwest, Steinbrenner and Gessel (1956) found tractor skid trails covered 26.1 percent of a logged area. In the same region, Dyrness (1965) determined 62 percent of a logged site received some form of soil disruption. In north central Washington, Wooldridge (1960) found tractor logging left 29 percent of the ground surface disturbed. On several tractor-logged sites east of the Cascade Mountains in Oregon and Washington, Garrison and Rummell (1951) found deep soil disturbance (in excess of 2.5 cm, but often to a depth of 30 to 60 cm) averaged 15 percent; combined deep and shallow disturbance was 21 percent. The values reported above pertain to single entries. With repeated thinnings or partial cuts the area relegated to tractor trails increases markedly.

Compaction

The Importance of Compaction in Wildland Management

Soil compaction may be defined as the packing together of soil particles, resulting in an increase in soil density through a decrease in pore space (Lull 1959). Chancellor (1976) considered an agricultural soil compacted when the proportion of total pore volume to total soil volume is inadequate for maximum plant growth or efficient management. From a hydrological viewpoint, a soil might be considered compacted when it results in unnatural rates of overland flow that increase short-term watershed yields and accelerate erosion.

Soil compaction exists in nature: snowpack weight, tree root expansion, and wildlife trampling can compact soils (Lull 1959, Greacen and Sands 1980). Chancellor (1976) noted some soils naturally shrink and condense upon drying. In some instances, compaction may have beneficial effects. If soil aeration, strength, and nutrients are not limiting plant growth, but moisture is, compaction may increase amount of soil water available for plants (Lull 1959, Rosenberg 1964, Greacen and Sands 1980). A certain degree of compaction might also aid seedling establishment by providing firm seedbeds for rooting (Hyder and Sneva 1956).

The wildland manager is chiefly concerned with the deleterious consequences of compaction on plants, watershed runoff, and erosion. This type of compaction is usually human-caused, resulting from forest harvest, slash-disposal, and silvicultural operations; from trampling by domestic livestock; and from impact of human feet and recreational vehicles (Lull 1959).

Compaction is not a phenomenon confined to forests and rangelands. Rosenberg (1964) and Chancellor (1976) cite numerous cases where agricultural yields were affected by vehicular compaction. Research into compaction on agricultural soils has applicability to wildland situations; however, there are differences in degree of compaction that occurs on wildlands, and in the ability of the manager to ameliorate the problems (Greacen and Sands 1980). In the forest situation, tree felling and yarding impose unique loads on soils; heavy mechanized equipment, together with pushing, pulling, and lifting of logs, exert extraordinary soil pressures; degree of variability of compaction and other forms of disturbance is much greater on forest soils because distribution of traffic is uneven; and deep soil ameliorative practices are made difficult by presence of stumps, roots, and trees (Greacen and Sands 1980). Also, forest soil densities on high producing sites are generally quite low, making them particularly vulnerable to compaction (Lull 1959, Froehlich 1973).

Some of the earliest studies into compaction and its effects on forest growth were conducted in the Pacific Northwest in the 1950's by Steinbrenner (1955), Steinbrenner and Gessel (1955), Forristall and Gessel (1955), Steinbrenner and Gessel (1956), and Youngberg (1959). Extensive reviews of wildland soil compaction have been conducted by Lull (1959), and more recently by Greacen and Sands (1980).

The Compaction Process

Soil compaction from mechanized equipment occurs when applied stress exceeds a soil's shearing strength. The load proceeds to sink into the ground, pressing the soil both downward and outward. Settlement stops when equilibrium is reached between stress and soil resistance. In this process soil grains are pressed together (Li 1956).

During logging, compaction from tractors occurs from pressures and deformations exerted by wheels and treads, as well as by skidded logs. Ground pressure values for crawler tractors are commonly computed by dividing total weight of the machine by its contact area with the ground. Froehlich (1973) noted crawler tractors range in weight between 4,500 and 16,300 kg, with an average ground pressure of 40 to 90 kilopascals (6 to 13 lb/in^2). Ground pressure exerted by vehicles with pneumatic tires, such as rubber-tired skidders, is considered roughly equal to tire inflation pressure (Hillel 1980). Static ground pressures of rubber-tired skidders are generally somewhat higher than those of crawler tractors or flexible-track skidders (Froehlich 1973, Greacen and Sands 1980). These static ground contact pressures may be multiplied several times by machine bouncing and vibration, by slipping and shearing action of lugs and tracks, and by load size and distribution (Froehlich 1973, Chancellor 1976, Greacen and Sands 1980, Hillel 1980).

As a medium for plant growth, soil might be conceived of as a flexible tank that stores and conducts nutrient-laden water and oxygen, and that deforms with root expansion (Vomocil and Flocker 1961). Detrimental compaction restricts the functions of storage and conductance by reducing the volume and continuity of the larger soil pores (Hillel 1980). Froehlich (1973) noted loss of macroporosity is closely paralled by decreases in soil infiltration and permeability. Increased soil strength and diminished pore diameter of compacted soils physically impedes root expansion (Gill 1961). Compaction also influences a soil's heat capacity and thermal conductivity, which can affect plant establishment and growth (Raney and Edminster 1961, Rosenberg 1964).

Compaction Measurement

A variety of means have been developed to measure soil compaction; unfortunately, no single method has proved "ideal." Soil strength is usually measured with a penetrometer (Chancellor 1976). Hillel (1980) noted the usefulness and universality of penetrometer measurements remain limited by lack of a standard design and standardized procedures. Bulk density is a commonly used index of soil compaction (Bodman and Constantin 1965). Soil density can be determined by core, clod, or excavation methods, which consist essentially of drying and weighing a known volume of soil; or by nuclear probe, an *in situ* method (Blake 1965). Measurement of change in soil density, though perhaps a more direct assessment of compaction, is typically less sensitive than measurement of change in soil fluid conductivity (Steinbrenner 1955, Lull 1959, Vomocil and Flocker 1961). Infiltration and permeability rates are particularly meaningful in terms of a soil's suitability as a medium for plant growth (Vomocil and Flocker 1961). However, infiltration measurements are typically arduous and time-consuming, are often inaccurate (Parr and Bertrand 1960), and can be affected by many factors other than compaction, such as soil surface sealing and soil reaction to minerals in the water (Chancellor 1976). Several forms of the air permeameter have been developed to determine soil macropore space in the field (Tanner and Wengel 1957, Steinbrenner 1959). Gifford et al. (1977) found moderate correlation (r = 0.86) between air permeameter readings and bulk density of undisturbed soil cores. Inaccuracies in measurement were found to result from improper contact of the permeameter with the soil and from disturbance of the soil during measurement.

Soil Factors That Affect Compaction

The primary soil factors that influence compaction are soil texture, structure, moisture, and organic matter content.

Soil Texture. Soils that contain a wide variety of particle sizes are more vulnerable to compaction than those with a limited range in particle sizes (Froehlich 1973). Assessing compactibility of artificial mixtures of varying particle sizes, Bodman and Constantin (1965) obtained greatest densities with mixtures having loamy sand textures.

Soil Structure. Generally, well-structured soils with low bulk densities are easily compactible (Lull 1959). On sandy loam soil in western Oregon, Froehlich (1973) found surface density changed from 0.65 to 1.03 g/cm^3 within the first three trips of a low ground-pressure skidder. The abrupt density increase was attributed to low initial soil bulk density coupled with high moisture content.

Soil Moisture. Water loosens a soil's interparticle bonds and behaves as a lubricant to reduce internal friction; hence, water lowers a soil's resistance to compaction (Hillel 1980). Every soil appears to have an "optimum" moisture content at which maximum density is achieved. Below this optimum, further compaction can be produced with a greater compactive effort, but beyond this level, density may actually decrease (Froehlich 1973, Hillel 1980). For soils ranging from clays to sandy loams, optimum compaction generally occurs midway between soil moisture tensions approximating field capacity and permanent wilting point (Froehlich 1973).

On a loblolly pine stand, Moehring and Rawls (1970) found bulk density of the surface layer of tractor skid trails, formed under wet weather conditions, increased 13 percent over that of undisturbed areas. Macropore space of the wet-logged soils decreased 49 percent. Under dry logging conditions, bulk density and macropore space were not significantly altered. Steinbrenner (1955) found one trip with a crawler tractor over moist soils caused a drop in soil permeability equivalent to four trips on dry soils. After four trips, the moist soil was nearly impervious to water.

Soil Organic Matter. A soil's compactibility generally decreases with increasing levels of organic matter. For silt loam and sandy clay loam soils, Free et al. (1947) found those soils containing the most organic matter were compacted to a lesser degree by a given compactive effort at a given moisture content, and moisture content at which maximum compaction occurred was higher.

On 14 forest and range soils in California, Howard et al. (1981) found soils with the least organic carbon (an index of soil organic matter) were most susceptible to compaction.

Compaction on Tractor-Logged Areas

In the Pacific Northwest most studies of forest soil compaction have been conducted in the highly productive region west of the Cascade Mountains. Steinbrenner and Gessel (1955, 1956) investigated the effects of tractor logging on clay loam and silty clay loam soils in southwestern Washington. On nine recently logged sites, cutover areas exhibited an average 35 percent loss in permeability, 11 percent drop in macropore space, and little change in bulk density, relative to soils of undisturbed areas. Tractor roads showed a 92 percent decrease in permeability, 53 percent loss of macropore space, and a 35 percent increase in bulk density. On a tractor-logged clearcut in Oregon, Dyrness (1965) found bulk density of compacted soil, which occurred on 27 percent of the logged unit, increased 62 percent over that of undisturbed soils. Large increases in surface bulk density were attributed to exposure of denser subsoil. Froehlich (1976) evaluated compaction by small crawler tractor on a young Douglas-fir stand. Bulk density of major tractor trails on clay loam soil was 1.26 g/cm^3, whereas density of undisturbed areas was 1.04 g/cm^3. Highest density observed on major skid trails was 1.64 g/cm^3.

For nine logged areas on the Atlantic Coastal Plain, Hatchell et al. (1970) found mean infiltration rates for secondary skid trails, primary skid trails, and log decks were reduced 78, 89, and 90 percent, respectively, using undisturbed soils as a comparison. Bulk density increased only one-half as much on secondary skid trails as on primary trails.

Forest soil compaction and its effect on plant growth can be long-lasting. On a sandy clay loam soil in central Oregon, Froehlich (1979) determined soil densities at 7.6 and 15.9 cm depths were 18 percent greater than those of adjacent, undisturbed soils, 16 years after thinning by tractor. Ponderosa pine trees with moderate impact in their rooting zones (i.e., 11 to 40 percent of the root zone affected by a 10 percent or greater increase in soil density) exhibited a 6 percent reduction in growth rate. Heavily impacted trees (i.e., 40 percent or more of the root zone affected) showed a 12 percent growth rate reduction. Little recovery from compaction was apparent on the site. On a Douglas-fir stand logged 32 years previously, Wert and Thomas (1981) found compaction persisted at depths of 20 and 30 cm over 25 percent of the site. For forests along the Atlantic Coastal Plain, Hatchell et al. (1970) determined average time for log decks and primary skid trails to return to density of undisturbed soils to be 18 years. Dickerson (1976) estimated tractor wheel ruts in a logged pine-hardwood forest in Mississippi required 12 years to recover from compaction; soil disturbed by log passage needed 8 years for recovery.

Effect of Compaction on Tree Seedling Growth

Compaction can heavily impair tree seedling germination, establishment, and growth. Garrison (1960) found ponderosa pine seedlings most prevalent on areas lightly skidded by tractors. No seedlings that germinated on barren skid trails lived to the 7th year after logging. In western Oregon, average height growth of two-year-old Douglas-fir seedlings planted on tractor roads was 42 percent less than seedlings growing on undisturbed cutover areas. Bulk densities of the tractor roads were substantially higher than those of undisturbed soils. Poor seedling growth on the roads was attributed to inadequate soil aeration and nitrogen deficiencies (Youngberg 1959). Steinbrenner and Gessel (1956) found skid roads on tractor-logged areas in southwestern Washington were poor growing sites for conifer seedlings. Seedling stocking on skid roads was reduced by nearly 50 percent, and number of established seedlings was reduced by nearly two-thirds, relative to tractor cutover areas. Adverse changes in soil physical properties, including permeability, macropore space, and density, as well as extreme frost heaving were considered major causes of poor seedling growth. Hatchell et al. (1970) found loblolly pine seedlings collected in the third growing season from the middle of skid trails had one-half to one-third the weight of seedlings from undisturbed soils; seedlings growing in tractor wheel ruts and tracks were lighter than those growing in the middle of trails. Retarded seedling growth was attributed to poor aeration and increased mechanical resistance brought about by compaction.

Compaction can also affect herbaceous plant growth. Barton et al. (1966) observed a compacted soil layer depressed growth and seed yield of three grass species by limiting root penetration and volume of soil from which moisture could be extracted.

Frequency of Travel

Greatest compaction damage often occurs with the first few tractor passes. Steinbrenner (1955) found a major drop in soil permeability after four trips by tractor on dry soils; little change in permeability occurred through the rest of ten trips. Froehlich (1978) investigated compaction by an FMC high speed- low ground pressure skidder on a sandy loam soil in eastern Oregon. The first few trips increased surface density by 11 percent with only minor density changes occurring with additional passes. For soils with a wide range of textures, Hatchell et al. (1970) found an average of 2.5 vehicle trips resulted in surface densities within 10 percent of densities attained by nine trips.

Prevention and Amelioration of Soil Disturbance and Compaction

Implementation of measures to prevent and ameliorate compaction, erosion, and other forms of logging-induced soil disturbance must be viewed in terms of sustained forest productivity and site stability. Unfortunately, although forest managers may recognize the relationship between long-term productivity and excessive soil disruption, detailed information on that relationship-- upon which management decisions can be based-- is often scarce (Greacen and Sands 1980). Methods for reducing impact of mechanized equipment on forest soils may be grouped into measures to be taken before, during, and after machines are on the land.

Before Logging-- Managing Natural Soil Factors

Maintenance of soil organic matter might be considered by the forest manager as a long-term management aim (Greacen and Sands 1980). Organic matter not only increases a soil's resistance to compaction, it adds nutrients to the soil, promotes increased water-holding capacity, and fosters soil water transmission (Taylor and Ashcroft 1972). Greacen and Sands (1980) recommended avoidance of severe slash burns that destroy surface organic matter, and advocated encouragement of biotic soil-forming factors such as earthworms. Organic materials such as bark might be incorporated into the soil to improve physical condition and lower compactibility (Moehring 1970, Greacen and Sands 1980).

During Logging-- Traffic Control

Allow Vehicle Entry Only Under Proper Soil Moisture Conditions.

"Trafficability"-- the capacity of a soil to stand up to traffic-- is largely a function of soil moisture (Satterlund 1972). Timing of vehicle entry to correspond with a site's trafficability is one of the most effective measures available to the forest manager to minimize soil damage (Satterlund 1972, Froehlich 1973, Chancellor 1976). However, the effect of variations in moisture content is not the same for all soils. Fine-grained, imperfectly drained, cohesive soils are easily compacted and displaced when wet, whereas course, non-cohesive soils do not compact readily when wet (Satterlund 1972). Excessively dry soils are more susceptible to displacement (Moehring 1970), and dry, course soils are also more susceptible to densification from vibration of vehicles (Hillel 1980).

Use Machines With Low Ground Pressures or That Otherwise Cause Minimum Disturbance. Compaction increases with equipment weight and degree of vibration. Very slow moving vehicles also promote compaction (Chancellor 1976). Type of vehicles used for harvest may affect extent of areal disturbance on a site. Froehlich (1978) reported skidding with a high speed- low ground pressure tractor resulted in marked reduction in amount of area covered with skid trails, compared with disturbance achieved by conventional crawler tractors. In Idaho, Haupt (1960) found use of small ("D-4"-type) tractors caused a considerably larger area to be occupied by haul roads and landings than when larger tractors were used for harvesting.

Carefully Plan Road Systems. Mass soil movement and surface erosion can often be traced to poor road design, location, and construction (Satterlund 1972). Width of access roads should be minimized. Narrow access roads not only retain more productive ground for timber production, they are cheaper to build, require less maintenance, are more stable from a watershed standpoint, and are aesthetically less offensive (Pfister 1969).

Keep Vehicles Off Steep Slopes. Garrison and Rummell (1951) observed deep soil disturbance from traffic was 2.8 times greater on slopes of 40 percent or more. Fewer possible locations for logging roads and landings on steep terrain caused skid trails to be longer and more heavily traveled. Heavy disturbance on steep slopes also resulted from frequent tractor side-slipping. Erosion damage can be considerably reduced by orienting trails along the slope contour (Dyrness 1965).

Consider Alternative Logging Systems. In general, the less contact with the forest floor, the less soil damage done by yarding and skidding (Satterlund 1972). Numerous studies have reported diminished site disturbance when cable systems are used for timber harvesting rather than tractors. Aulerich et al. (1974) found skyline logging left 8 percent of an area in skyline roads, whereas thinning by tractor left 16 to 27 percent of a stand in skid trails. No soil compaction was detected where the skyline system was used, while on tractor skid trails increases in bulk density occurred to the 30 cm depth. Comparing tractor and high-lead harvesting systems in the Oregon Cascade Mountains, Dyrness (1965) found the two methods produced roughly equivalent amounts of slightly and deeply disturbed soil, but the tractor-logged site exhibited three times more area compacted.

Logging on snow has been suggested as an alternative means of minimizing ground disturbance from timber harvest (Lull 1959, Satterlund 1972). Advanced yarding systems, such as helicopter and balloon logging, probably incur the least soil damage

(Satterlund 1972); however, operating costs of these methods are often prohibitive (Adams and Froehlich 1981).

Depending on the Circumstances, Either Disperse or Confine Machine Impact Over the Logged Area. Extent and degree of compaction depend, in part, on strategy of extraction routes (Greacen and Sands 1980). Permanent skid trails might be established for use during all entries onto the stand (Adams and Froehlich 1981). Greater compaction on a smaller area might be preferable to less compaction on a greater area (Greacen and Sands 1980). Hatchell et al. (1970) advised that on moist, medium textured soils, where considerable damage is likely to occur from the first vehicle trip, traffic should be confined to a few primary trails. The trails might later be restored through cultivation. Conversely, dispersing traffic over the stand might be considered for dry, course textured soils in order to minimize vehicle impact on any one spot. Traffic dissemination might improve the seedbed for regeneration by exposing mineral soil, and would reduce the need for restorative practices (Pomeroy 1949, Hatchell et al. 1970).

Spread Surface Runoff. While machines are still on the logging site, water barriers should be built on skid trails to deflect damaging runoff (Greacen and Sands 1980).

Afterwards-- Rehabilitation

Natural recovery of compacted soils to approximate pre-logged conditions may take several decades (Froehlich 1973). Soil recovery will be a function of extent and severity of initial disturbance, as well as soil type and physical processes of the soil environment, which include shrinking, slaking, settling, vertical erosion into cracks, swelling, freezing, thawing, and animal traffic (Heinonen 1977, Greacen and Sands 1980). The soil recovery process may be assisted by a number of rehabilitative procedures:

Cultivation. Practices for correcting poor physical condition include plowing, which inverts and mixes the soil; disking, which cuts and mixes the soil surface; subsoiling, which loosens deep compaction; and landscaping, which corrects soil displacement and drainage problems (Moehring 1970). Rainey and Edminster (1961) cautioned mechanical loosening to reverse compaction is often short-lived: the soil may return to the same density it had before treatment.

Plants to Loosen and Condition Soil. Some tree species and brush may be used for penetrating and breaking up dense soil (Lull 1959, Froehlich 1973). The practice of seeding skid trails and other areas with grass may be beneficial in speeding recovery of compacted soil (Froehlich 1973).

Revegetation by Seeding

Revegetating logging areas by seeding, usually with perennial grasses, has become a standard method of regaining watershed protection and forage resources lost during tree harvest and slash disposal operations. Denham (1960) concluded failure to seed logged areas would eventually result in the loss of as much as 50 percent of the grazing capacity of interior Northwest forests. The advantages of seeding have been enumerated by several authors (Gjertson 1949, Rummell and Holscher 1955, Denham 1960, Seely 1960, MacLauchlan 1966, Sassaman 1972, Sassaman and Fight 1975). These benefits include:

1. produces a plant cover that stabilizes soils, preventing erosion and downstream sedimentation;
2. restores and/or increases site forage production for domestic livestock and wildlife;
3. prevents invasion of undesirable plants, including early-drying, fire-hazardous species;
4. provides habitat for game and non-game wildlife species;
5. enhances appearance of logged sites;
6. maintains roads for fire control and future logging entries;
7. controls establishment of unwanted brush and stagnant "dog-hair" tree stands.

A possible adverse effect of seeding is that it may prevent germination of desirable seral species (Strickler and Edgerton 1976).

In the eastside forests of Oregon and Washington, revegetation success is highest when seeding is done within one year after time of disturbance. Areas logged in winter and early spring should be seeded in early spring. Those places logged in summer and fall should be seeded in late fall (Gjertson 1949). A survey of 52 seeded logged sites in the Northwest revealed 80 percent of the seedings were medium or better in success, and 45 percent were good or very good in success (Gjertson 1949).

Kind of species to seed depends on the management objective. MacLauchlan (1966) recommended seed mixtures used for permanent stabilization of erodible areas include a rapid-developing short-lived species, as well as a heavy root-producing, long-lived perennial. The rapid-developing species would furnish quick ground cover and soil protection, allowing the slower developing perennial to establish itself. Legumes for nitrogen fixation might also be included in the mixture. Denham (1960) recommended seeding perennial grasses because: (1) perennials would exclude low-value annual invader species; (2) perennials are less flammable than annuals; and (3) perennials are more dependable in providing succulent green forage at the time it is needed.

Hall (1980) suggested high producing improved species such as orchardgrass (Dactylis glomerata) be seeded on Eastside logged areas to maximize forage production. Miller and Krueger (1976) found timothy (Phleum pratense) and orchardgrass were the most successful introduced species on a clearcut mixed conifer forest in northeastern Oregon; these species were especially palatable to livestock and big game. Gjertson (1949) recommended seed mixtures for ponderosa pine forests in the Northwest be built around timothy and orchardgrass, because the seeds of these species are small, rapidly starting, and are amenable to broadcasting. Orchardgrass has the additional advantage of being shade tolerant.

Hedrick et al. (1968) suggested artificial seeding should optimally provide maximum forage compatible with satisfactory tree regeneration. To reduce competition with trees, the authors recommended against the use of aggressive perennials such as orchardgrass and smooth brome (*Bromus inermis*), advocating, instead, short-lived improved species and native bunchgrasses such as blue wildrye (*Elymus glaucus*). Gjertson (1949) cautioned against revegetation with sod-forming species, which might preclude tree regeneration.

Little research has been conducted on use of native indigenous species for regenerations. Klock (1969a, b) found elk sedge (*Carex geyeri*), a principal component of ponderosa pine and mixed conifer forests in Oregon and Washington, could be successfully cored, transplanted, and cultivated. The highly fibrous root system and drought tolerance of elk sedge might make it desirable for quick establishment as an erosion control on disturbed or depleted forest grazing lands.

Reseeding with introduced species will typically increase overall forage production on forested range. Reid (1965) noted 2200 to 3400 kg/ha of air-dry forage might be expected from seeded logging areas in pine forests. Hall (1980) stated that orchardgrass and timothy seeded at a rate of 3.4 to 4.5 kg/ha on a clearcut mixed conifer forest should result in 0.4 ha/AUM of forage; this yield will be reduced to 2.0 ha/AUM in 15 years as native species replace the seeded forages. Sassaman (1972) estimated seeding forested ranges in the Northwest should produce 0.4 ha/AUM, which could be sustained throughout the timber rotation.

Control of erosion is a primary intent of many seedings. Interestingly, Helvey and Fowler (1979) found no consistent relationship between seeding and vertical soil displacement on a steep clearcut in the northern Blue Mountains of Oregon, even though plant cover on the seeded areas was double that of unseeded areas.

SECTION 1:

CHARACTERISTICS OF HERBACEOUS VEGETATION AND SOILS ON SEEDED TRACTOR SKID TRAILS IN AN EASTERN OREGON FOREST

Abstract

Understory vegetation and soil values were compared between seeded skid trails and undisturbed areas on a mixed conifer stand approximately 6 years following logging and slash piling by tractor. Understory vegetation production of seeded trails was 66 percent greater than that of undisturbed areas. However, belowground biomass of undisturbed areas, vegetated chiefly with rhizomatous species, was three times that of skid trails. Litter cover and litter depth on skid trails was lower than that of undisturbed areas by 27 and 71 percent, respectively. Loss of soil protection by belowground biomass and litter on skid trails was partially mitigated by high infiltration and saturated hydraulic conductivity (SHC) rates, and maintenance of plant cover by seeded species. Bulk density was not significantly different between treatments; however, substantially less infiltration and SHC rates, and greater soil strength on skid trails implied some soil densification occurred. Organic matter content of skid trails was 54 percent less in the surface 3 cm, but was higher between 9 and 24 cm, relative to undisturbed areas. Soil moisture retention was not significantly different between treatments. A low correlation (r = -0.17) was determined between soil strength at the 5-10 cm depth and herbaceous growth on skid trails.

Additional Index Words: volcanic ash soils, forest grazing, belowground biomass, soil disturbance

CHARACTERISTICS OF HERBACEOUS VEGETATION AND SOILS ON SEEDED TRACTOR SKID TRAILS IN AN EASTERN OREGON FOREST

Introduction

The fact that skid trails typically occupy 25 percent or more of the ground surface of tractor logged sites (Froehlich 1973) attests to their importance in forest management. In the Pacific Northwest, ground disturbance from tractor logging has been found to detrimentally affect yield and composition of understory forage species (Denham 1960, Garrison 1965, Young et al. 1967) and establishment and growth of commercial trees (Youngberg 1959, Froehlich 1979, Wert and Thomas 1981). Deterioration of the plant growth environment on logged areas most often occurs on compacted skid trails and landings. Soil disturbance from timber harvest and slash disposal operations may also displace nutrient-rich topsoil and accelerate erosion, resulting in lowered site fertility and increased sedimentation in downstream channels and catchments (Moehring 1970, Brown 1979). The deteriorated condition of plants and soils on logged areas may persist for many years (Froehlich 1979, Wert and Thomas 1981).

In eastern Oregon, bare areas resulting from tractor logging may remain devoid of herbaceous plant cover for several years, or may be invaded by weedy species, unless seeded (Garrison 1961, Hedrick et al. 1968). Skid trails seeded with grasses provide an important forage base for livestock and big game while tree overstory returns (Hall 1980). Little information is available concerning plant growth and soil properties, including compaction, on skid trails in Oregon's eastside forests.

The purpose of this study was to compare herbaceous vegetation and soil properties between seeded skid trails and undisturbed areas in a mixed conifer forest. A site was chosen which was considered representative of the mixed conifer-pinegrass (Pseudotsuga-Abies-Calamagrostis) community type (Hall 1973), important for its commercial timber production in the Blue Mountains. These mountains provide summer grazing for about 100,000 cattle (Bos taurus) and sustain large herds of mule deer (Odocoileus hemionus hemionus) and Rocky Mountain elk (Cervus elaphus nelsoni) (Skovlin et al. 1976). The study was conducted 6 years after the site had been tractor-logged; slash was machine-piled and burned a year following harvest. Specific objectives were: (1) compare production of above- and belowground herbaceous biomass, and herbaceous cover between treatments; (2) compare litter cover, litter depth, soil organic matter, soil saturated hydraulic conductivity and soil moisture retention between treatments; (3) assess extent of compaction on skid trails according to indices of bulk density, penetrometer resistance, saturated hydraulic conductivity, and infiltration, and (4) relate penetrometer resistance to understory growth.

Study Site

The study site is a 1.5 ha forested area on the Malheur National Forest in the southern Blue Mountains of eastern Oregon. The site faces east with a 15 percent slope at an elevation of 1700 m. Average annual precipitation is 760 mm, most of which falls as snow between October and May. Mean January temperature is -4.8°C; mean July temperature is 15.8°C (Carlson 1974).

Ponderosa pine (Pinus ponderosa Laws.), grand fir (Abies grandis (Dougl.) Lindl.) and Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) compose the overstory of the undisturbed native community. Principal understory species are pinegrass (Calamagrostis rubescens Buckl.), elksedge (Carex geyeri Boott), and heartleaf arnica (Arnica cordifolia Hook.). These three rhizomatous species often combine to form a dense turf, to the near exclusion of other species. Shrubs are scarce.

The soil is a loamy skeletal, mixed, frigid Typic Xerochrept, characterized by a shallow (5 - 15 cm) silt loam surface layer derived from volcanic ash, and an underlying cobbly silt loam dervied from basalt and andesite. Soil depth ranges from 30 to 90 cm.[a/] Ash-derived soils exhibit several unique properties, including low bulk densities, easily detachable articles, and high water holding capacity (Carlson 1974, Geist and Strickler 1978).

Commercial timber was logged from the site in the late 1950's. In August 1974, harvesting by crawler tractor reduced the overstory to about 20 percent in a shelterwood cut. In the summer of 1975, slash was machine-piled and burned. Machinery were allowed to

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[a/]Soil description provided by T. Sullivan, Soil Scientist, Malheur National Forest.

operate off primary skid trails to scarify the soil surface for tree regeneration. Forty-three percent of the site exhibited some form of soil disturbance. Ten percent of the site was committed to skid trails.

Following logging and slash burning, 3-4 kg/ha each of orchardgrass (Dactylis glomerata L.), mountain bromegrass (Bromus marginatus Nees.), intermediate wheatgrass (Agropyron intermedium (Host) Beauv.), and 1 kg/ha of timothy (Phleum pratense L.) were drilled into skid trails. Seeding rates are approximated from U.S. Forest Service records. Success of establishment of seeded species was considered representative of grass seedings on similar sites in the region. Though cattle grazed the site annually, livestock were excluded the year sampling was conducted.

Materials and Methods

Data were collected in the summer of 1980. Four sets of transects were arranged at regular intervals across the study site. A set consisted of 10 transects, 40 m long and spaced 10 m apart. Sets were positioned on the site so that transects were roughly perpendicular to the slope. "Potential" plots were assigned at 4 m intervals along the transects and field-checked. Those lying within skid trails and undisturbed areas were noted. From the pool of "potential" skid trail plots, 40 were randomly chosen for study. Forty plots were similarly selected for the undisturbed areas. A 0.5 m^2 plot was used. Skid trails were obvious primary tractor routes caused by repeated passage of machinery and logs.

Undisturbed areas were identified by an intact litter layer and strong predominance of native perennial vegetation.

Within each plot herbage production and composition data were collected by double sampling-weight estimate technique (Pechanec and Pickford 1937, Wilm et al. 1944). Plants were clipped by species at peak of growing season, oven-dried, and weighed. Shrubs and tree seedlings on both skid trails and undisturbed areas were scarce and therefore not measured. Areal spread of understory canopy and litter cover were occularly estimated on each 0.5 m^2 plot. Litter depth measurements were taken at four pre-designated points within the plot and averaged.

Soil resistance was measured by a proving ring penetrometer at four points within each plot at 0-5 and 5-10 cm depths. Following the 0-5 cm measurement, soil at each point was excavated to the 5 cm depth; then the lower reading was obtained. Surface litter was removed before readings were taken. Results were averaged by plot and converted to units of force (kilopascals).

On a random subsample of 12 plots within each treatment, the following properties were measured: belowground biomass, soil bulk density, soil infiltration rate, soil saturated hydraulic conductivity, percent soil organic matter, soil moisture retention, and soil particle distribution.

Belowground biomass was sampled with a 7.0 cm-diameter corer driven to 10 cm to obtain a 385 cm^3 core. This depth was based on the observation that nearly all roots and rhizomes of understory species were concentrated within the surface 10 cm. Samples were washed, oven-dried, and weighed. Ash weight was subtracted from dry weight to gain an ash-free value, which was converted to kg/ha.

Bulk density at three depths was measured by undisturbed core method (Blake 1965). Within both treatments two coring devices, differing in size of sample obtained, were used to take density samples. Core sample sizes were 71.5 cm^3 (core height = 3.5 cm) and 131.3 cm^3 (core height = 6.0 cm). Sampling depths are reported as depths to core mid-points: 3.2, 10.8, and 18.4 cm.

Infiltration rate was measured with a double-ring infiltrometer. Following removal of surface litter, a metal cylinder, 15.2 cm in diameter, was driven 4 cm into the soil. This cylinder was nested within a 50 cm-diameter ring, also driven into the soil, creating a surrounding zone to which water was added. Standing water was maintained in this outer zone throughout the sampling period. Water was then added to the inner ring to a level of 10 cm. Time in which the water level dropped 7 cm was recorded. This procedure was repeated to obtain a second reading. Because prior sampling had disturbed the soil within the established 0.5 m^2 plots, infiltration runs were conducted outside and adjacent to the plots.

Saturated hydraulic conductivity (SHC) was determined on undisturbed cores from the 3.2 cm depth. Cores with volumes of 71.5 and 131.3 cm^3 were collected within each treatment and placed under a constant head of 7 cm of water until flow passing through the samples stabilized. Darcy's equation (Hillel 1980) was used to calculate SHC from amount of leachate collected beneath the cores over a given time.

Percent organic matter at five depths (0-3, 3-6, 6-9, 9-12, 12-24 cm) was determined by Walkley-Black method (Allison 1965).

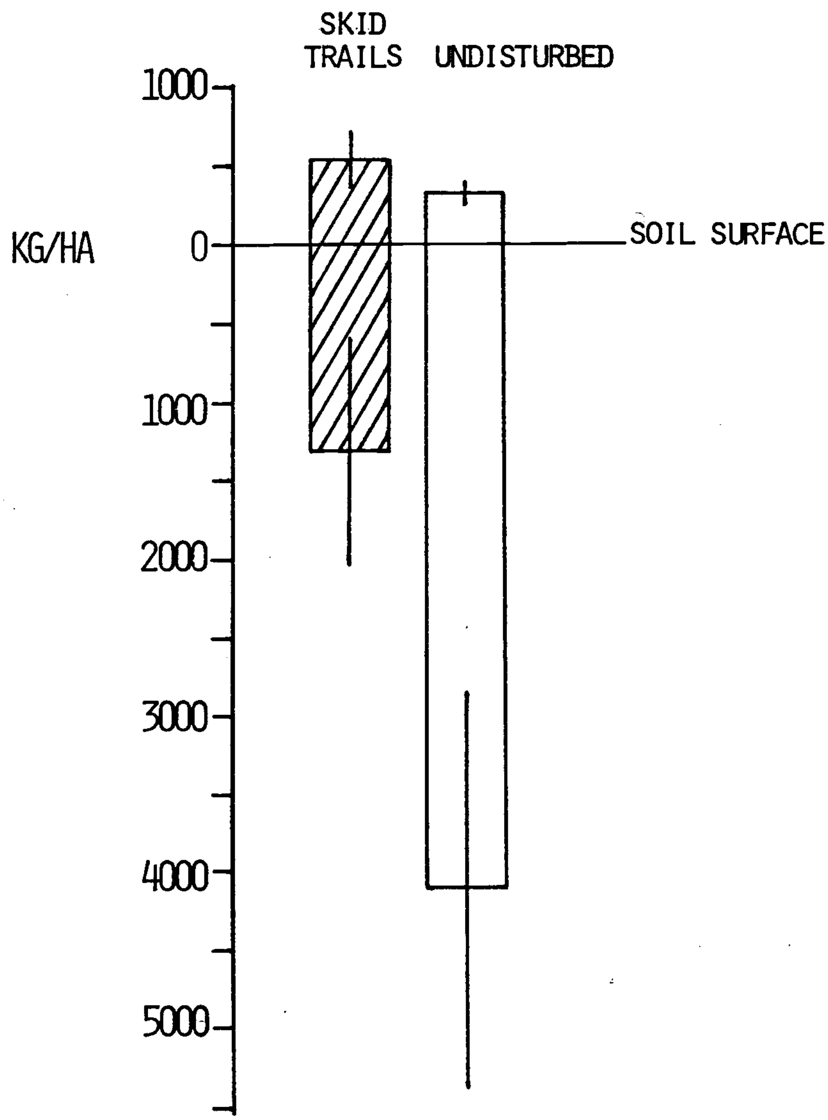
Moisture retained at four soil water potentials was determined by pressure plate apparatus on cores from the 10.8 cm depth. The -15.0 bars reading was obtained after cores were disturbed by sieving through a 2 mm screen. From the soil fraction > 2 mm, organic matter was floated off, leaving a remainder of coarse mineral fragments which were dried and weighed.

Mean treatment differences were tested at the 0.05 and 0.01 probability levels using Student's "t" procedure.

Results

Seeded skid trails produced 66 percent more aboveground herbage per unit area than undisturbed areas: 551 and 332 kg/ha, respectively (Figure 1). This difference was statistically significant (< 0.01). Vegetative composition of skid trails was 90 percent graminoids and 10 percent forbs by dry weight. Ninety percent of skid trail production was comprised of seeded species. Orchardgrass and intermediate wheatgrass were present respectively on 82 and 80 percent of skid trail plots; together, these two species accounted for 65 percent of total skid trail herbaceous yield. Composition of undisturbed areas was 83 percent graminoids, 17 percent forbs. Pinegrass and elksedge constituted nearly all graminoid production on undisturbed areas.

FIGURE 1-- ABOVE- AND BELOWGROUND HERBACEOUS PRODUCTION OF SKID TRAILS AND UNDISTURBED AREAS. VERTICAL LINES INDICATE ONE STANDARD DEVIATION. BOTH ABOVEGROUND AND BELOWGROUND TREATMENT MEANS DIFFER SIGNIFICANTLY (0.01 PROBABILITY LEVEL).



Difference between treatments in belowground production of roots and rhizomes was significant (< 0.01), and sharply contrasted with aboveground figures (Figure 1). Belowground production of skid trails (1300 kg/ha) was only 32 percent of the root and rhizome production of undisturbed areas (4100 kg/ha). Thirty percent of the total biomass of the seeded skid trails was aboveground, compared with only 7 percent for undisturbed areas.

In spite of the differences in aboveground production, treatments had similar herbaceous coverages of about 20 percent; yet several other properties important for soil stabilization and plant growth were altered on skid trails (Tables 1 and 2). Litter cover and litter depth of skid trails were respectively 27 and 71 percent below amounts on undisturbed areas.

Infiltration rate of skid trails in the first run was 60 percent less than that of undisturbed areas. This difference was significant (< 0.05). Treatment means for the second infiltration run (on soils heavily soaked from the first run) were not significantly different (> 0.05); however, skid trails exhibited a trend (< 0.1) toward lower infiltration rate in this second run.

Saturated hydraulic conductivity (i.e., soil permeability) could be considered the minimum infiltration rate expected of a soil (Vomocil and Flocker 1961). The SHC rate of soil cores from the surface of skid trails was significantly (< 0.05) 66 percent below that of cores from undisturbed areas.

No significant differences (> 0.05) in bulk density were detected between treatments at three depths. There was a trend

Section 1: Table 1-- Ground cover characteristics of tractor skid trails and undisturbed areas.

Property	Units	Skid trail			Undisturbed		
		$\bar{x}$	s	n	$\bar{x}$	s	n
Understory cover	percent	19	8	40	22	10	40
Litter cover**	percent	70	52	40	96	7	40
Litter depth**	cm	.7	.5	40	2.4	1.3	40

Legend: $\bar{x}$ = sample mean; s = standard deviation; n = sample size.

**Treatment means differ significantly at the 0.01 probability level, as tested by Student's "t" procedure.

Section 1: Table 2-- Compaction indices for tractor skid trails and undisturbed areas.

		Skid trails			Undisturbed		
Property	Units	$\bar{x}$	s	n	$\bar{x}$	s	n
Infiltration	cm/hr						
1st run*		19.0	15.5	12	48.0	43.4	12
2nd run		15.5	15.2	12	34.5	29.7	12
Saturated hydraulic conductivity**	cm/hr	6.7	4.1	11	19.7	11.9	12
Bulk density	g/cm^3						
3.2 cm		0.78	0.12	12	0.68	0.16	12
10.8 cm		0.85	0.20	12	0.89	0.08	12
18.4 cm		0.86	0.23	11	0.92	0.12	11
Resistance	k/Pa						
0 to 5 cm		690	260	40	760	190	40
5 to 10 cm**		1050	210	39	900	190	40

Legend: $\bar{x}$ = sample mean; s = standard deviation; n = sample size.

*, **Treatment means differ significantly at the 0.05 and 0.01 levels, respectively, as tested by Student's "t" procedure.

(< 0.10) toward higher bulk density of the surface (core mid-depth of 3.2 cm) of skid trails.

Penetrometer resistance did not differ significantly (> 0.05) between treatments at the 0-5 cm depth. Resistance on skid trails was significantly (< 0.01) 17 percent higher than undisturbed areas at the 5-10 cm depth. Interpretation of the 0-5 cm reading was made difficult by resistance caused by roots and rhizomes, which could not be separated from resistance caused by soil densification. Rhizome-root resistance was most apparent on undisturbed areas, occupied by native turf. Since the indigenous rhizome layer was chiefly confined to the upper 5 cm, the 5-10 cm penetrometer readings were more reliable indices of soil resistance.

Soil moisture and rock contact can influence penetrometer readings (Gifford et al. 1977). Skid trail soil moisture averaged 8.5 percent at time of penetrometer measurement, compared with 19.6 percent for undisturbed areas. Greater evapo-transpiration potential on skid trials, resulting from greater leaf area and reduced litter, may have accounted for this moisture difference. Rock contact by the penetrometer was a minor problem. Cores taken from the 10.8 cm depth contained 17.3 and 15.3 percent coarse mineral fragments on skid trails and undisturbed areas, respectively. This difference was not statistically significant (>0.05), and it was assumed rock contact did not affect relative penetrometer values and other compaction measurements.

Regression analysis was used to ascertain the relationship between aboveground herbaceous production and penetrometer resistance at the 5-10 cm depth on 39 skid trail plots: a statistically low correlation coefficient of -0.17 was determined.

Organic matter content in the surface 3 cm of skid trail soils was less than half that of undisturbed areas (Figure 2). Treatment percentages were identical at the 3-6 cm depth. At lower depths a reversal occurred: organic matter content of skid trails at 9-12 and 12-24 cm was 74 and 87 percent higher, respectively, than that of undisturbed areas.

Significant shifts in moisture retention values were not evident between treatments (>0.05; Table 3). Available water (difference between -0.1 bar and -15.0 bars soil water potentials) was nearly identical for the two treatments.

Discussion

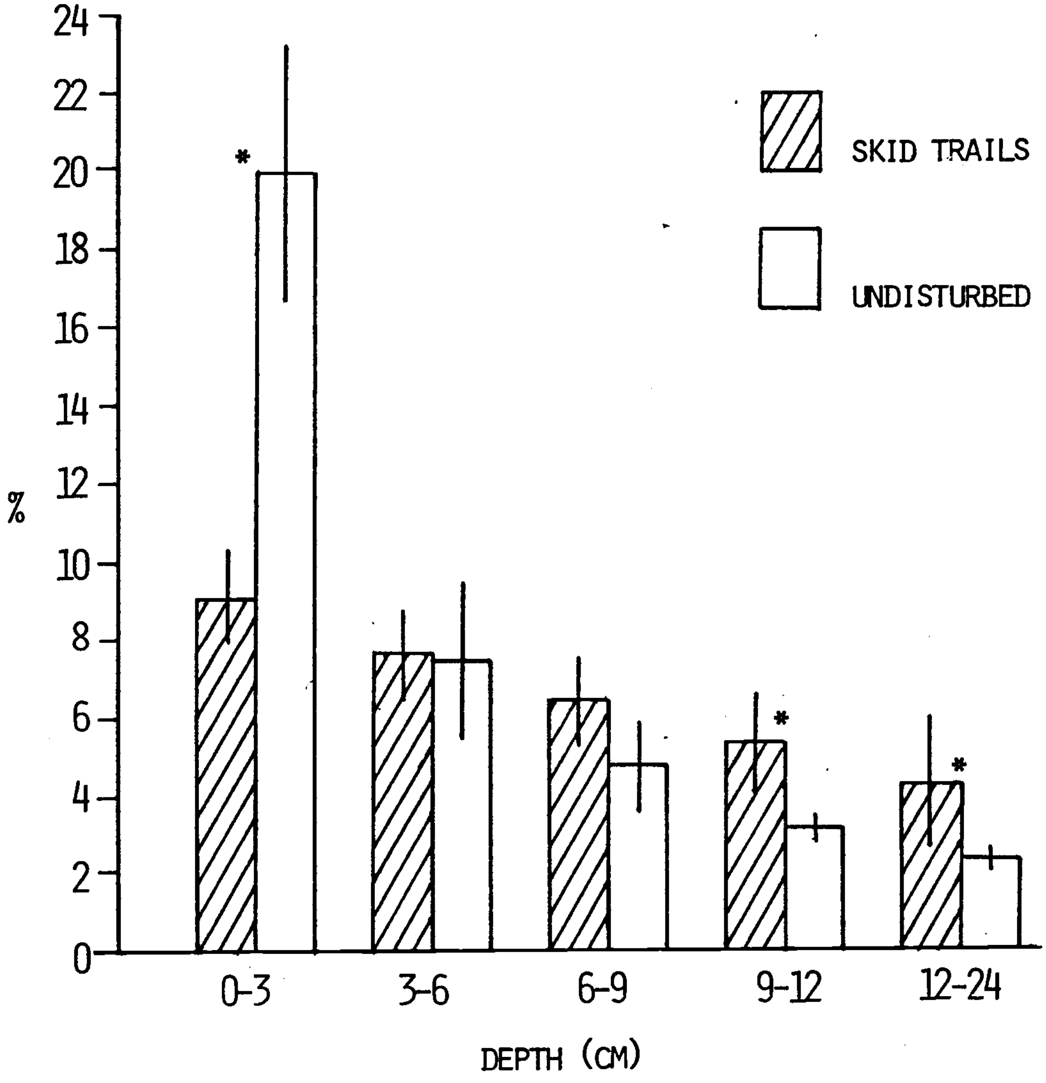
Forage

Skid trails on the site provided a substantial forage base for grazing animals, both wild and domestic. Introduced grasses supplied considerably more forage than native vegetation of adjacent undisturbed areas; moreover, the introduced species are generally considered more palatable to large herbivores than native species. Forage production on skid trails was similar to that determined on a seeded clearcut in a mixed conifer forest in northeastern Oregon (Miller and Krueger 1976).

Topsoil Protection

Protection of topsoil should be a key concern of forest

FIGURE 2-- PERCENT ORGANIC MATTER CONTENT OF SKID TRAILS AND UNDISTURBED AREAS. VERTICAL LINES INDICATE ONE STANDARD DEVIATION. ASTERISK (*) INDICATES TREATMENT MEANS DIFFER SIGNIFICANTLY (0.05 PROBABILITY LEVEL).



Section 1: Table 3-- Percent soil water retention (by volume) of tractor skid trails and undisturbed areas at the 10.8 cm sample depth.

	Skid trails			Undisturbed		
Water potential	$\bar{x}$	s	n	$\bar{x}$	s	n
- 0.1 bar[a]	39.7	6.0	12	38.8	3.4	12
- 0.3 bar[a]	28.9	5.4	12	27.9	3.5	12
- 1.0 bar[a]	23.1	7.0	9	22.3	2.6	10
-15.0 bars[a]	14.1	2.7	10	13.4	1.2	10
0.1 to -15.0 bars	25.6			25.4		

Legend: $\bar{x}$ = sample mean; s = standard deviation; n = sample size.

[a]No significant differences found between treatments at the 0.05 level as tested by Student's "t" procedure.

managers in the region. Geist and Strickler (1978) found a disproportionate amount of nutrients in the upper 30 cm of soils in the northern Blue Mountains. The authors determined nitrogen, phosphorus, and several other elements essential for plant growth were held near the soil surface, chiefly in the form of organic matter. A large proportion of organic matter was found in the top several centimeters of undisturbed soils on the site of this study. Under dry conditions, ash-derived soils are highly vulnerable to wind erosion when natural cover is removed (Geist and Strickler 1978). Seeding skid trails maintained the percentage of plant cover afforded by the native understory. However, substantially less amounts of belowground biomass and litter on the skid trails suggested a decrease in erosion protection, despite a 5 to 6 year recovery period. Skid trail seedings often had a patchy appearance, especially where orchardgrass dominated. In these areas thick clumps of seeded species were commonly interspersed with bare areas where litter and vegetation were nearly absent.

Infiltration and Saturated Hydraulic Conductivity

Topsoil loss from water erosion on skid trails was no doubt partially mitigated by high soil water conductance, as well as a relatively gentle slope. Infiltration rate is an important indicator of a soil's vulnerability to water erosion: when infiltration rate is exceeded, surface runoff will occur, fostering erosion and soil nutrient depletion (Dyrness 1965). Though skid trail infiltration rates were less than half those of undisturbed areas, they were high in comparison with storm intensities projected for the region. For instance, estimated precipitation for a one-hour storm with a 100-year return period in the area is 2.54 cm (National Oceanic and Atmospheric Administration 1949-1978). Flood-type infiltrometers, such as the one used in this study, tend to over-estimate natural infiltration rates, and caution should be employed when comparing flood infiltrometer rates with storm intensities (Wilm 1941, Burgy and Luthin 1956). Nevertheless, skid trail soils appeared capable of absorbing most precipitation. SHC rates on skid trails and undisturbed areas were also well above the 100-year storm level. On a clearcut in northeastern Oregon, Helvey and Fowler (1979) observed evidence of overland flow on deeply disturbed skid trails, but not on less-disturbed soils over a 20-month period. Surface soils in their study were of volcanic ash origin. In the present study signs of severe water erosion, such as gullies and plant pedestals, were not evident on skid trails.

Soil Density and Compaction

The surface soil density of 0.68 g/cm^3 for undisturbed soils closely matched 0.69 g/cm^3 reported by Geist and Strickler (1978) for the top 15 cm of ash-derived soils in the northern Blue Mountains. For the same depth interval, these authors reported a density of 0.89 g/cm^3 for residual soils of basalt origin, matching the figure found in this study for undisturbed soil at the 10.8 cm depth. The sharp increase in bulk density within the first 11 cm of undisturbed soil on the study site probably reflected both a shift from volcanic ash to residual basalt-andesite influence, and a quick drop in organic matter with increasing depth.

Trends toward compaction were evident on the skid trails. Markedly lower infiltration and SHC rates on the skid trails suggested macropore space of skid trail soils was substantially less than that of the undisturbed soils (Froehlich 1973). Higher penetrometer resistance on skid trails, relative to the undisturbed soils, implied tighter packing of soil grains on the skid trail soils.

Penetrometer Resistance and Plant Growth

The low correlation between penetrometer resistance and vegetation production on skid trails indicated soil strengths were below those that would impede grass and forb growth. Greacen and Sands (1980) pointed out increased soil strength resulting from compaction may produce a more compact root system, but as long as air, water, and nutrients are in ample supply, plant growth will not be restricted.

Organic Matter

Depleted amounts of organic matter in the upper 3 cm of skid trails, relative to undisturbed areas, implied an important nutrient loss. Surface organic matter may have been removed from skid trails through soil scalping by machinery at time of harvest and slash removal, by wind and water erosion, or by oxidation resulting from environmental changes brought about by tree canopy reduction (Trimble and Tripp 1949). Some organic material was apparently transferred to lower depths. Higher organic matter content between 12 and 24 cm of the skid trails denoted mixing occurred at least to this level. Though soil moisture content at time of logging was not known, relatively deep mixing of organic matter can probably be ascribed to machines operating on the site when soil was dry and somewhat loose.

Summary and Conclusion

For the tractor-logged mixed conifer stand examined in this study, soil densities, measured on soil core samples, were not greatly altered on skid trails, relative to nearby undisturbed areas. Nevertheless, markedly lower rates of soil water infiltration and saturated hydraulic conductivity on the skid trails, as well as a higher average soil strength, implied skid trail soils were subject to some densification.

Compaction and other forms of soil disturbances from logging are important to the extent they influence plant growth, long-term soil nutrient and watershed storage values, and soil erodibility. Herbaceous plant growth of tractor skid trails on the site was not impaired at soil strengths encountered. Soil densities and strengths at which growth of understory and trees is suppressed-- and whether these conditions exist in Eastside forests under present logging practices-- remain to be determined. Comparable water retention values between treatments suggested moisture storage characteristics were not altered on skid trails.

Revegetation of skid trails with introduced grasses improved the forage base and matched understory cover of the site's undisturbed areas. Soil-binding roots and rhizomes, along with plant litter, were substantially less on skid trails; however, erosion from skid trails, though not quantified, appeared minimal.

Organic matter has been noted by others as a major nutrient source in Blue Mountain soils; therefore, loss of organic matter from the first several centimeters of the site's skid trails could potentially affect plant growth. Though some organic material was distributed to lower depths in skid trails, this buried nutrient supply may have been largely unavailable to the shallow root systems of herbaceous species. The relationship between organic matter levels and plant growth on logged areas in the region requires further study.

SECTION 2:

SOIL PROPERTIES OF A TRACTOR-LOGGED CUTOVER IN AN EASTERN OREGON MIXED CONIFER FOREST

Abstract

Soil and watershed-related characteristics of non-skid trail areas of a mixed conifer forest were examined 6 years following tractor logging and 5 years after slash had been machine-plied and burned. Four disturbance classes were identified, based on degree of disruption of soil and ground cover. Compaction, measured by bulk density, penetrometer resistance (strength), infiltration, and saturated hydraulic conductivity (SHC), was not evident. Infiltration and SHC rates for all disturbance classes were high, relative to storm intensities projected for the region. Litter cover of general disturbance areas and berms was respectively 45 and 68 percent below that of undisturbed areas. Slash fire rings were virtually litter-free. Organic matter content of berms and fire rings at the 0-3 cm level was respectively 38 and 60 percent lower than that of undisturbed areas, but was significantly higher at some subsurface levels. Bulk density of disturbed soils was inversely correlated with organic matter content. Soil moisture retained at four water potentials, coarse mineral fragment content, and fine earth particle size distribution did not differ statistically among treatments.

Additional Index Words: volcanic ash soils, erosion, compaction, soil organic matter, watershed

SOIL PROPERTIES OF A TRACTOR-LOGGED CUTOVER IN AN EASTERN OREGON MIXED CONIFER FOREST

Introduction

The 8.1 million hectares of forest east of the Cascade Mountains in Oregon and Washington (Denham 1960) are a source of quality timber (Gedney 1963), provide crucial forage for domestic livestock, and support large herds of deer (*Odocoileus hemionus hemionus*) and Rocky Mountain elk (*Cervus elaphus nelsoni*) (Skovlin et al. 1976). Ground disturbance from tractor logging and slash clean-up may adversely affect soil physical, chemical, and biological characteristics, thus restricting growth of commercial trees and understory forage. In the Pacific Northwest, Wert and Thomas (1981) found reduction of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) growth on skid roads and zones adjacent to skid roads caused an overall stand volume loss of 11.8 percent. Three years following tractor logging in an Eastside mixed coniferous forest, Hedrick et al. (1968) noted herbage cover was reduced 80 percent on areas of heavy soil disturbance, which occupied 15 percent of the site.

Tractor logging can compact and displace soils, making them more vulnerable to erosion (Moehring 1970). In an eastern Oregon forest, Froehlich (1978) found one to three trips with a high-speed log skidder increased soil density in the surface 5 cm by 11 percent.

The purpose of this study was to evaluate ground disturbance resulting from tractor logging and residue clean-up on a mixed conifer forest stand. The study was conducted 6 years after the site was logged, and 5 years after slash was machine-piled and burned. Study objectives were: (1) determine degree of compaction on the site by the indices of soil bulk density, penetrometer resistance (soil strength), infiltration, and saturated hydraulic conductivity; (2) assess the effect of logging disturbance on factors related to plant growth and watershed quality, including litter cover and depth, soil organic matter content, moisture storage, particle size distribution, coarse mineral fragment content, infiltration rate, and saturated hydraulic conductivity; and (3) determine areal extent of ground disturbance on the study site.

Soil disturbance on the tractor cutover area, apart from primary skid trails, was the focus of this study. Soil and vegetation characteristics on the site's skid trails were reported by Snider and Miller (in press).

Study Site

The study was conducted on a 1.5 ha site, considered representative of the mixed conifer forests of the region. The site is located at an elevation of 1700 m on the Malheur National Forest in the southern Blue Mountains. It faces east with an average slope of 15 percent. Average annual precipitation is 760 mm, most of which falls as snow between October and May. Mean

January temperature is -4.8°C; mean July temperature is 15.8°C (Carson 1974).

The site is a mixed conifer-pinegrass (Pseudotsuga-Abies-Calamagrostis), ash soil community type (Hall 1973). The undisturbed native community is two-layered: ponderosa pine (Pinus ponderosa Laws.), grand fir (Abies grandis (Dougl.) Lindl.), and Douglas-fir compose the overstory. Principal understory species are pinegrass (Calamagrostis rubescens Buckl.), elk sedge (Carex geyeri Boott), and heartleaf arnica (Arnica cordifolia Hook.). These three rhizomatous species often combine to form a dense turf, to the near exclusion of other species. Shrubs are scarce.

The soil is a loamy skeletal, mixed frigid Typic Xerochrept, characterized by a shallow (5-15 cm) silt loam surface layer derived from volanic ash, overlaying a cobbly silt loam derived from basalt and andesite. Soil depth ranges from 30 to 90 cm.[a/] Ash-derived soils exhibit several unique properties, including low bulk densities, easily detachable particles, and high water holding capacities (Carlson 1974, Geist and Strickler 1978).

Commercial timber was logged from the site in the late 1950's. In August 1974, harvesting by crawler tractor reduced the overstory to approximately 20 percent. In the summer of 1975, slash was machine-piled and burned. Tractors were allowed to "wander" off primary skid trails to scarify the soil surface for tree

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[a/]Soil description supplied by T. Sullivan, Soil Scientist, Malheur National Forest.

regeneration.

Areas of major disturbance were artificially seeded to orchard-grass (*Dactylis glomerata* L.), intermediate wheatgrass (*Agropyron intermedium* (Host) Beauv.), and mountain bromegrass (*Bromus marginatus* Nees.) at a rate of 3-4 kg/ha for each species. Timothy (*Phleum pratense* L.) was applied at 1 kg/ha. These rates are estimated from U.S. Forest Service records. At time of sampling vegetation on the disturbed areas was composed of a blend of native and seeded species. Cattle grazed the site annually but were excluded the year sampling was conducted.

Materials and Methods

Data were collected in the summer of 1980, 6 years after logging, and 5 years after slash disposal on the site. Disturbance on the cutover was separated into four classes: *General disturbance* was defined as those areas of light to moderate disturbance where some of the litter layer had been removed and mineral soil exposed. Ground disturbance in this broad class varied from areas where a tractor had passed once, leaving a single tread imprint, to places where multiple passes had occurred. *Berms* were characterized by heavy soil displacement where soil had been formed into mounds at least 10 cm high. *Fire rings* were areas where the soil surface had been altered by slash piling and burning. *Undisturbed* areas were identified by an intact litter layer and near-total to complete dominance by native perennial vegetation.

Areal percentage of each disturbance class on the study site was determined by line-intercept method. Four sets of transects were arranged at regular intervals across the site. A set consisted of 10 transects, 40 m long and spaced 8 m apart. The sets were positioned on the site so that transects were roughly perpendicular to the slope.

Along these same transects, "potential" plots were established at 4 m intervals. Each "potential" plot was field-checked and consigned to a disturbance class. Forty actual plots for each disturbance class were randomly chosen from this pool of "potential" plots. A 0.5 m^2 rectangular plot was used.

On each plot, litter cover, litter depth, and penetrometer resistance were measured. Percent litter cover was occularly estimated. Litter depth was averaged from four measurements taken at pre-designated points within the plot. Soil resistance at 0-5 and 5-10 cm depths was measured with a proving ring penetrometer at four pre-established points within the plot. Surface litter was removed before readings were taken. Soil was excavated to the 5 cm depth to obtain the 5-10 cm reading. Results for each depth were averaged and converted to units of force (kilopascals). Before penetrometer measurements were taken on fire rings, unconsolidated mineral "powder" (a product of hot slash burns) was brushed away from the surface.

On a random subsample of 12 plots within each treatment, bulk density, saturated hydraulic conductivity (SHC), infiltration, and organic matter were measured. Two core sizes were used for bulk density and SHC determinations: 71.5 cm^3 (core height = 3.5 cm) and 131.3 cm^3 (core height = 6.0 cm). Bulk density at three depths was calculated for undisturbed cores (Blake 1965). Sampling depths are reported as depths to core mid-points, i.e., 3.2, 10.8, and 18.4 cm. Saturated conductivity was determined for undisturbed cores taken from the 3.2 cm depth. Cores were placed under a constant 7 cm head of water until flow of water passing through them stabilized. Darcy's equation (Hillel 1980) was used to calculate SHC from amount of leachate collected beneath the cores over a given time.

Infiltration was sampled with a double-ring infiltrometer. Following removal of surface litter, a metal cylinder, 15.2 cm in diameter, was driven 4 cm into the ground. This cylinder was nested within a 50-cm diameter metal ring, also driven into the soil, creating a surrounding zone in which standing water was maintained throughout the sampling period. Water was added to the inner ring to a level of 10 cm. Time in which the water level dropped 7 cm was recorded. This procedure was immediately repeated to obtain a second reading. Because prior sampling had disturbed the area within the 0.5 m^2 plots, infiltration runs were conducted outside and adjacent to the plots.

Percent organic matter at 5 depths was determined by the Walkley-Black method (Allison 1965).

Further tests were made on 71.5 cm^3 soil cores taken at the 10.8 cm depth from the subsample plots previously mentioned. From each of the four disturbance classes, 10 to 12 cores were collected, on which the following properties were measured: soil moisture retention, Walkley-Black organic matter, percent organic matter > 2 mm, particle size distribution, percent coarse (> 2 mm) mineral fragments, and bulk density. Soil water content at four water potentials was determined by pressure plate apparatus. Water content at -0.15 bars was measured after cores were disturbed by sieving through a 2 mm screen. From the soil portion > 2 mm, organic matter was floated off, oven-dried, and weighed. The remaining mineral portion was also dried and weighed. Particle size distribution of the fine earth fraction (< 2 mm) of these same samples was determined by sieving and pippette methods (Day 1965). Percent organic matter and bulk density were determined by methods previously described.

Regression analysis was used to ascertain the influence of Walkley-Black organic matter, organic matter > 2 mm, and "combined" organic matter (a sum of the two percentages) on bulk density of the 40 cores, segregated by treatment.

Analysis of variance and Tukey's procedure were used to test mean treatment differences at the 0.05 probability level.

Results

Forty-three percent of the site exhibited some form of soil disruption. Areas of general disturbance, berms, and fire rings occupied 23, 8, and 2 percent of the site, respectively. (Ten percent of the site was committed to skid trails.)

Evidence of compaction, from four types of measurement, was lacking on any of the disturbed treatments, when compared with the undisturbed areas. In some instances, observations of compaction were lower on berms and fire rings than on the undisturbed areas (Tables 1 and 2).

Though treatment differences were large for both infiltration runs, high sample variability reduced sensitivity of statistical comparison, and no significant differences (> 0.05) were determined. Saturated hydraulic conductivity (SHC) of cores taken from the soil surface showed no significant differences (> 0.05) among treatments.

Bulk density of berms at the 10.8 cm depth was significantly (< 0.05) 19 percent lower than that of undisturbed areas. At this depth general disturbance areas and fire rings exhibited trends toward lower bulk densities, relative to undisturbed areas.

Penetrometer resistance in the surface 5 cm of areas of general disturbance, fire rings, and berms was respectively 34, 49, and 70 percent below that of undisturbed areas. The high resistance of undisturbed areas reflects the contributing influence of roots and rhizomes of the native species. Resistance caused by this rhizomatous mat just below the soil surface could not be segregated from that caused by soil density. Since the rhizome layer was confined chiefly to the upper 5 cm, readings at the 5-10 cm level furnished a more reliable assessment of soil resistance. At this lower depth, resistance of fire rings and berms were respectively 31 and 38 percent below that of undisturbed areas. Resistance of

Section 2: Table 1— Soil infiltration, saturated hydraulic conductivity (SHC), and penetrometer resistance values of logging disturbance classes.

Characteristic	Units	General	Berm	Fire ring	Undisturbed
			Means		
1st infil.	cm/hr	23.4 a[a/]	99.6 a	14.5 a	48.0 a
2nd infil.	cm/hr	17.0 a	54.6 a	13.2 a	34.5 a
SHC	cm/hr	12.2 a	23.6 a	14.6 a	19.7 a
Resist., 0-5 cm	kPa	500 b	230 a	390 b	760 c
Resist., 5-10 cm	kPa	960 b	560 a	620 a	900 b
			Standard deviations		
1st infil.		23.4	189.2	8.4	43.4
2nd infil.		16.3	77.5	11.4	29.7
SHC		9.4	28.5	19.7	11.9
Resist., 0-5 cm		220	180	270	190
Resist., 5-10 cm		260	260	280	190
			Sample sizes		
1st infil.		12	12	12	12
2nd infil.		12	12	12	12
SHC		12	12	11	12
Resist., 0-5 cm		39	40	40	40
Resist., 5-10 cm		39	40	39	40

[a/] Numbers in rows followed by the same letter are not significantly different at the 0.05 level.

Section 2: Table 2--Soil bulk density values of logging disturbance classes at three levels. Depths are mid-points of sample cores.

Depth, cm	General	Berm	Fire ring	Undisturbed
		Bulk density, g/cm^3		
3.2	0.69 a[a/]	0.66 a	0.72 a	0.68 a
10.8	.86 ab	.72 a	.81 ab	.89 b
18.4	.93 a	.89 a	.85 a	.92 a
		Standard deviation		
3.2	0.14	0.17	0.14	0.16
10.8	.13	.18	.13	.08
18.4	.14	.15	.13	.12
		Sample size		
3.2	11	12	11	12
10.8	12	12	11	12
18.4	11	11	11	11

[a/] Numbers in rows followed by the same letter are not significantly different at the 0.05 level.

general disturbance areas at this depth was significantly (<0.05) higher than that of berms and fire rings, but not of undisturbed areas.

Litter cover differed significantly (<0.05) among all treatments (Table 3). Litter cover of general disturbance areas and berms was respectively 45 and 68 percent less than that of undisturbed areas. Litter depth of general disturbance areas and berms was below that of undisturbed areas by 58 and 71 percent, respectively (Table 3). Fire rings were practically litter-free 5 years after slash burning.

Organic matter content of undisturbed areas was high at the surface but dropped abruptly with increasing soil depth (Table 4). At the 0-3 level, organic matter content of berms and fire rings was significantly (<0.05) lower than that of undisturbed areas. Organic matter content of berms between 6 and 9 cm was double that of other treatments; at the 9-12 cm level it was approximately twice that of undisturbed and general disturbance areas. Fire rings held 117 percent more organic matter than undisturbed areas between 12 and 24 cm. Berms and fire rings frequently contained buried layers of partially decomposed tree needles and other surface litter.

Organic matter content of cores taken at the 10.8 cm level significantly (<0.05) correlated, in an inverse manner, with bulk density on the disturbed treatments, but not on undisturbed areas (Table 5). The relationship of bulk density to organic matter could

Section 2: Table 3-- Litter cover and depth values of logging disturbance classes.

Characteristics	General	Berm	Fire rings	Undisturbed
		Means[a]		
Litter cover (percent)	53 c[b]	31 b	4 a	96 d
Litter depth (cm)	1.0 b	0.7 b	0.1 a	2.4 c
		Standard deviations		
Litter cover (percent)	29	26	9	7
Litter depth (cm)	1.0	1.0	.1	1.3

[a] Sample size is 40 for all means.

[b] Numbers in rows followed by the same letter are not significantly different at the 0.05 level.

Section 2: Table 4-- Soil organic matter content of logging disturbance classes.

Depth	General	Berm	Fire ring	Undisturbed
		Means, percent[a/]		
0 to 3 cm	12.7 ab[b/]	12.3 a	8.0 a	19.9 b
3 to 6 cm	6.9 a	10.4 a	7.8 a	7.5 a
6 to 9 cm	5.3 a	10.9 b[c/]	5.5 a	4.7 a
9 to 12 cm	3.7 a	7.3 b	4.8 ab	3.1 a
12 to 24 cm	2.6 ab	3.8 ab	5.0 b	2.3 a
		Standard deviations		
0 to 3 cm	7.9	5.0	7.1	6.3
3 to 6 cm	2.2	5.0	4.8	4.0
6 to 9 cm	3.1	6.7	3.6	2.2
9 to 12 cm	1.8	3.7	3.0	0.8
12 to 24 cm	0.9	1.8	4.1	0.4

a/Sample size is 12 except where indicated.

b/Numbers in rows followed by the same letter are not significantly different at the 0.05 level.

c/Sample size is 11.

Section 2: Table 5-- Constants (a), regression coefficients (b), and coefficients of determination (r^2) in equations $1/y = a + bx$, for predicting soil bulk density (y) from three "types" of organic matter (x).

		Values for "x"		
Disturbance	Parameter	Walkley-Black[a/]	2 mm[b/]	Combined[c/]
Undisturbed	a	1.0747	1.1104	1.0718
	b	0.0306	0.1562	0.0282
	r^2	0.1332	0.2394	0.1655
General Disturbance	a	0.8913	1.0643	0.9171
	b	0.0784	0.3447	0.0650
	r^2	0.7028[d/]	0.6648[d/]	0.7080[d/]
Berm	a	0.7645	1.2484	0.9590
	b	0.0955	0.1014	0.0522
	r^2	0.8739[d/]	0.9309[d/]	0.9562[d/]
Fire ring	a	1.0856	1.2439	1.0954
	b	0.0460	0.0767	0.0369
	r^2	0.5397[d/]	0.3151	0.5845[d/]

[a/] x = Organic matter determined by the Walkley-Black method.

[b/] x = Organic matter >2 mm.

[c/] x = Combined organic matter, obtained by summing Walkley-Black and organic matter >2 mm.

[d/] r^2 values are significant at the 0.05 level of probability.

be described by the regression equation:

$$1/y = a + bx$$

where:

y = bulk density

x = organic matter

Higher coefficients of determination were generally obtained when "combined organic matter"-- the sum of Walkley-Black organic matter and organic matter >2 mm-- was used as the x variable.

Moisture retention values did not significantly (>0.05) differ among disturbance classes (Table 6); nor were there differences in sand, silt, and clay percentages among treatments (Table 7). Coarse mineral fragment (>2 mm) values for general disturbance areas, berms, fire rings, and undisturbed areas were 22.3, 17.0, 15.8, and 15.3 percent, respectively. These values did not differ statistically (>0.05).

DISCUSSION

Disturbance Classes

Amount of litter covering areas of general disturbance on the site were well below that of undisturbed areas. Thus, general disturbance areas, which comprised nearly a quarter of the study site, may have been somewhat more vulnerable to erosion than the undisturbed areas. Outside this disparity, soil properties of general disturbance areas did not greatly differ from those of the undisturbed areas.

Section 2: Table 6-- Percent soil moisture content by volume at four water potential levels among logging disturbance classes. "Available water" values are included.

Water potential	General	Berm	Fire ring	Undisturbed
	Means, percent by volume[a]			
-0.1[b] bars	40.8	35.8	33.8	38.8
-0.3[b]	30.5	26.4	27.5	27.9
-1.0[b]	24.1	22.9	20.8	22.3
-15.0[b]	13.2	12.4	12.1	13.4
Available water (-0.1 to -15.0)	27.6	23.4	21.7	25.4
	Standard Deviations			
-0.1	5.1	7.3	9.4	3.4
-0.3	4.2	6.4	5.9	3.5
-1.0	3.9	6.3	2.3	2.6
-15.0	1.8	1.5	2.3	1.2
	Sample Sizes			
-0.1	12	12	11	12
-0.3	12	11	11	12
-1.0	11	8	10	10
-15.0	10	10	10	10

[a] Determined on core samples from the 10.8 cm depth.

[b] No significant differences among treatments were detected by Tukey's test at the 0.05 level of probability.

Section 2: Table 7-- Sand, silt, and clay fractions of logging disturbance classes.

Fraction	General	Berm	Fire ring	Undisturbed
		Means, percent[a/]		
Sand (2.0 -0.05 mm)[b/]	39.4	39.8	42.1	42.1
Silt (0.05 -0.002 mm)[b/]	51.1	48.6	48.7	48.3
Clay (< 0.002 mm)[b/]	9.5	11.7	9.2	9.6
		Standard deviations		
Sand	4.3	4.9	2.6	2.3
Silt	3.7	3.3	2.6	2.0
Clay	2.0	4.1	1.7	1.4

[a/] Determined at the 10.8 cm depth from 10 core samples from each treatment.

[b/] No significant differences among treatments were detected by Tukey's test at the 0.05 level of probability.

Berms were places of considerable soil mixing, as indicated by relatively low amounts of surface organic matter, as well as the presence of identifiable litter and high levels of organic matter in their subsurface profiles. The churned soil of berms may provide favorable seedbeds, and incorporation of surface organic matter might hasten mineralization and nutrient availability (Moehring 1970). However, nutrients released by organic matter buried at deeper levels may be unavailable to the shallow root systems of herbaceous species. Berm crests were sometimes thickly vegetated; vegetation and litter were often scarce or absent on berm slopes. As areas of loose, exposed soils, berms were potentially vulnerable to puddling and erosion (Moehring 1970, Geist and Strickler 1978); however, accelerated water erosion on berms was not visibly evident. Some soil scalping probably occurred to form the berms, signaling possible long-term damage to site growth potential.

Like the berms, fire rings were areas of heavy soil disruption. On some fire rings it was visually obvious soil had been scraped into piles along with slash. High levels of organic matter in the subsurface of fire rings were indicative of buried turf and litter. Despite a half-decade of recovery, a litter layer was absent on the fire rings, and plant growth was extremely restricted. Below the surface layer of mineral powder, fire rings exhibited soil properties conducive to plant growth. Suitability of fire rings for revegetation could be enhanced by machine scarification that would mix the sterile powder with underlying soils.

Compaction

Much compaction damage from logging machinery often occurs with the first few vehicle passes (Hatchell et al. 1970, Froehlich 1978). Absence of compaction was probably due to several site factors. These include:

1) Volcanic ash influence. According to Carlson (1974), ash soils are difficult to compact.

2) Dry soil condition at time of vehicle operation.

3) A high percentage of organic matter in the top several centimeters of the site's soil at time of logging. On 14 California forest and range soils, Howard et al. (1981) determined soils with the least organic carbon (an index of organic matter) were most susceptible to compaction. Similarly, high amounts of organic matter were correlated with low bulk densities on the disturbed portions of this study's cutover area.

4) Presence of litter as well as a tough mat of rhizomatous vegetation. At several locations in eastern and western Oregon, Froehlich (1978) observed presence of litter markedly decreased compaction from a low ground-pressure skidder.

Soil Water Conductance

Infiltration and SHC rates on both disturbed and undisturbed areas were high in comparison with regional storm intensities. Projected precipitation for a one-hour storm with a 100-year return period in the area is 2.54 cm (National Oceanic and Atmospheric Administration 1949-1978). "Flood"-type infiltrometers like the one used in this study, may overestimate natural infiltration rates (Wilm 1941). Nevertheless, soils on the cutover appeared capable of absorbing most of the precipitation reaching it, thus curtailing water erosion.

Soils of all disturbance classes generally exhibited high coefficients of variability (CV = standard deviation x 100/ sample mean) for infiltration and SHC rates. Coefficients of variability for berms were particularly high. High variability of water conductance rates implied a larger sample size was required for sensitive statistical comparison.

Conclusion

Soil physical properties, measured 5-6 years after logging disturbance, were not greatly affected on non-skid trail areas of the study site. The data suggest overall conditions suitable for plant growth were maintained, soil moisture retention characteristics were conserved, and erosion from the site was minimized.

Compaction of the ash/basalt-andesite soils of the site was probably reduced by logging under dry conditions, and by the natural characteristics of the forest floor and soil, including high organic matter content of the surface horizon. For areas of porous soils logged under dry conditions, Hatchell et al. (1970) advocated spreading traffic over the logged site to reduce the need for restorative practices (e.g., cultivation of compacted skid trails), and to improve the seedbed for tree regeneration by exposing mineral soil. Forest managers must weigh the benefits obtained from dispersing vehicle traffic against the possibility that "wandering tractors" will aggravate detrimental soil displacement.

Soil displacement, resulting from tractor movement and blade scalping during slash piling, was visually evident in berms and fire rings, which together comprised 10 percent of the site. Topsoil displacement can potentially lower a logged areas's long-term productivity (Moehring 1970), and should be a particular concern in the Blue Mountains, where a disproportionate amount of nutrients are held near the soil surface, mainly in the form of organic matter (Geist and Strickler 1978). The impact of soil displacement on the fertility of Eastside logged forests needs evaluation.

SUMMARY AND CONCLUSIONS

Empirical information is lacking for sound management of forests soils in the interior Pacific Northwest. Because this study was confined to one site in the southern Blue Mountains of eastern Oregon, interpretation of its results must be limited accordingly; however, its findings have implications for management of similar plant-soil systems in the region, and for future research.

Compaction of ash/basalt/andesite soils of the site was evident on skid trails by markedly lower soil water conductance rates, and higher soil strengths, relative to undisturbed areas. Most skid trail compaction probably resulted from compression by machinery and yarded logs. It is possible that mixing of denser subsoils with the surface mantle contributed to skid trail compaction. Some soil mixing occurred between 12 and 24 cm on skid trails, as indicated by higher amounts of organic matter at this level relative to undisturbed areas. It is notable that berms and fire rings, though subject to heavy soil mixing, were not compacted. Soil compaction measurements would also be higher where denser subsoils were exposed on skid trails as a result of topsoil scalping. Soil density measurements on core samples from skid trails and undisturbed areas did not statistically differ, in spite of relatively low sample variability within treatments. This suggests bulk density was a comparatively insensitive compaction measurement. There was no evidence of compaction on non-skid trail areas. Compaction on the site was probably minimized by a variety of factors: 1) naturally low compactibility of ash-derived soils, 2) high organic matter content and substantial litter cover at time of logging and slash piling, 3) dry soil conditions at time of logging, and perhaps 4) few number of passes over any given spot off the skid trails. Of the five disturbance classes, soils of the berms and slash fire rings exhibited the most variability in soil properties. The influence of periodic livestock grazing on site properties, such as soil compaction and vegetation and litter production, were not evaluated.

Herbaceous plant growth on the seeded skid trails was not inhibited by soil strengths encountered. Bulk densities were generally below 0.9 g/cm^3. Little research on the effect of compaction on growth of grasses has been reported. Barton et al. (1966) found yield of three forage grasses decreased as degree of compaction increased on a sandy clay loam in Texas; however, soil densities measured in their study were higher than 1.5 g/cm^3-- well above the highest densities found on skid trails in this study. When a soil is compacted the interaction between plants, soil strength, nutrient and water supply, and aeration is probably complex (Greacen and Sands 1980). For some low-density soils of volcanic origin, a certain degree of compaction may benefit plant growth by increasing availability of water to roots (Packard 1957). Research is clearly needed to identify soil densities and strengths at which understory vegetation and tree growth is restricted on Eastside forest soils, and to what extent these densities and strengths occur with present logging practices.

Soil moisture retention values were comparable among all disturbance classes, indicating soil water availability to plants was not altered. Infiltration and SHC rates were high in all disturbance classes relative to projected storm intensities. These high rates would likely preclude surface runoff and consequent erosion. Very rapid infiltration and SHC rates might denote excessive drainage, i.e., when the soil drains so fast that air quickly replaces moisture and soil becomes droughty. Excessive drainage may help explain lack of vegetation on most berm slopes. High coefficients of variability for water conductance values on all disturbance classes indicate the need for larger sample sizes for adequate statistical comparison.

Artificial seeding of skid trails increased the supply of palatable forage for wildlife and livestock, and established an understory cover comparable to that of undisturbed areas. The protective cover of litter on the disturbed areas was markedly lower than that of the undisturbed areas. On the seeded skid trails belowground biomass, a soil stabilizing factor, was two-thirds less than that of undisturbed areas. Nevertheless, water erosion was not visually evident on the site.

Some damage from topsoil scalping and displacement probably occurred on the site. Some organic matter was no doubt scraped from the surface of skid trails and other disturbance types and transported to berms and fire rings, which together comprised about 10 percent of the study area; the rest was either lost through oxidation and erosion, or was buried in place. Since organic matter is a prime nutrient source in many Blue Mountain soils, plant growth on logged areas could be inhibited if large amounts of organic matter are removed during harvest and clean-up operations. Depletion of surface organic matter would especially impede growth of shallow-rooted plants, including native and seeded forage species. The influence of soil displacement from logging activities on sustained site fertility and soil stability needs serious investigation.

In general, tractor logging did not have serious adverse effects on soil properties and herbaceous vegetation characteristics evaluated on the site. Damage from compaction appears to have been minimized by spreading tractor impact over the logging areas-- as opposed to confining traffic to primary skid trails. Some of the soil displacement that occurred could have been prevented if bulldozer blades had been kept at a proper height during slash clean-up, or an alternative method of slash disposal had been used.

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APPENDICES

APPENDIX A

Soil description for study area.

Horizon	Depth (cm)	Description (Colors are for moist soil)
01	0-2	Leaves, needles, and decomposing organic matter, covering 80-100 percent of the surface.
A1	0-8	Very dark brown (10YR2/2) silt loam; weak, very fine granular structure; soft (dry), very friable (moist), slightly sticky and slightly plastic (wet); no clay films; non-effervescent; clear, smooth boundary.
IIA1	8-38	Dark brown (7.5YR3/4) silt loam; weak, very fine granular structure; soft (dry), very friable (moist), slightly sticky and slightly plastic (wet); few thin clay films; non-effervescent; gradual, wavy boundary.
IIB2	38-64+	Dark brown (7.5 YR3/4) silt loam; weak, very fine granular structure; soft (dry), very friable (moist), slightly sticky and slightly plastic (wet); few thin clay films; 40 percent cobbles by field volume estimate; non-effervescent.

Location-- 2 km north of Crane Prairie Guard Station, Malheur National Forest, sec. 24, T. 16S, R. 34E.

Geology-- basalt and andesite, volcanic ash.

Slope-- 20 percent.

Aspect-- southeast.

Elevation-- 1700 m.

Drainage-- well to excessive.

Vegetation-- ponderosa pine, grand fir, Douglas-fir, pinegrass, elk sedge.

APPENDIX B

Herbaceous production of logging disturbance classes.

Class	General	Berm	Fire ring	Skid trail	Undisturbed
			Means, kg/ha[a]		
Graminoids	225	204	37	498	277
Forbs	48	68	12	53	55
Total	274[b]	271[b]	49	551	332
			Standard Deviations		
Graminoids	199	212	122	351	154
Forbs	46	79	18	103	49
Total	199	233	122	353	164

[a] Sample size is 40 for all means.

[b] Difference between sum of graminoid and forb classes, and total production figure is due to rounding.

APPENDIX C

Belowground biomass for five logging disturbance classes.

General	Berm	Fire ring	Skid trail	Undisturbed
		Means, kg/ha[a/]		
2020	1300	750	1300	4100
		Standard Deviations		
1710	1210	960	970	2480

[a/]Sample size is 12 for all means.

APPENDIX D

Understory vegetation cover of logging disturbance classes.

General	Berm	Fire ring	Skid trail	Undisturbed
		Means, percent		
16	13	3	19	22
		Standard Deviations		
9	8	4	8	10
		Sample Sizes		
39	40	40	40	40

APPENDIX E

Overstory canopy cover of logging disturbance classes.

General	Berm	Fire ring	Skid trail	Undisturbed
		Means, percent[a/]		
18.9	20.2	13.9	16.4	27.2
		Standard Deviations		
12.9	11.6	6.5	10.3	16.0

[a/] Canopy cover determined with Lemmon "type-C" densiometer. Sample size is 40 for all means.

APPENDIX F

Litter cover and litter depth of logging disturbance classes.

Characteristic	General	Berm	Fire ring	Skid trail	Undisturbed
			Means[a/]		
Cover, percent	53	31	4	70	96
Depth, cm	1.0	0.7	0.1	0.7	2.4
			Standard Deviations		
Cover, percent	29	26	9	52	7
Depth	1.0	1.0	0.1	0.5	1.3

[a/]Sample size is 40 for all means.

APPENDIX G

Bulk densities of five logging disturbance classes.

Depths, cm	General	Berm	Fire ring	Skid trail	Undisturbed
			Means, g/cm^3		
3.2	0.69	0.66	0.72	0.78	0.68
10.8	.86	.72	.81	.85	.89
18.4	.93	.89	.85	.86	.92
			Standard Deviations		
3.2	.14	.17	.14	.12	.16
10.8	.13	.18	.13	.20	.08
18.4	.14	.15	.13	.23	.12
			Sample Sizes		
3.2	11	12	11	12	12
10.8	12	12	11	12	12
18.4	11	11	11	11	11

APPENDIX H

Soil strength as measured by penetrometer on logging disturbance classes.

Depths, cm	General	Berm	Fire ring	Skid trail	Undisturbed
			Means, kilopascals		
0 to 5	500	230	390	690	760
5 to 10	960	560	620	1050	900
			Standard Deviations		
0 to 5	220	180	270	260	190
5 to 10	260	260	280	210	190
			Sample Sizes		
0 to 5	39	40	40	40	40
5 to 10	39	40	39	39	40

APPENDIX I

Soil infiltration rates of logging disturbance classes.

Run	General	Berm	Fire ring	Skid trail	Undisturbed
			Means, cm/hr[a]		
1st	23.4	99.6	14.5	19.0	48.0
2nd	17.0	54.6	13.2	15.5	34.5
			Standard Deviations		
1st	23.4	189.2	8.4	15.5	43.4
2nd	16.3	77.5	11.4	15.2	29.7

[a]Sample size is 12 for all means.

APPENDIX J

Soil saturated hydraulic conductivity of logging disturbance classes.

General	Berm	Fire ring	Skid trail	Undisturbed
		Means, cm/hr[a/]		
12.2	23.6	14.6	6.7	19.7
		Standard Deviations		
9.4	28.5	19.7	4.1	11.9
		Sample Sizes		
12	12	11	11	12

[a/]Samples taken at the 3.2 cm depth.

APPENDIX K

Soil moisture content by volume of logging disturbance classes at four soil water potentials.

Water potential	General	Berm	Fire ring	Skid trail	Undisturbed
			Means, percent by volume[a]		
- 0.1 bars	40.8	35.8	33.8	39.7	38.8
- 0.3	30.5	26.4	27.5	28.9	27.9
- 1.0	24.1	22.9	20.8	23.1	22.3
-15.0	13.2	12.4	12.1	14.1	13.4
			Standard Deviations		
- 0.1	5.1	7.3	9.4	6.0	3.4
- 0.3	4.2	6.4	5.9	5.4	3.5
- 1.0	3.9	6.3	2.3	7.0	2.6
-15.0	1.8	1.5	2.3	2.7	1.2
			Sample Sizes		
- 0.1	12	12	11	12	12
- 0.3	12	11	11	12	12
- 1.0	11	8	10	9	10
-15.0	10	10	10	10	10

[a] Samples taken at the 10.8 cm depth.

APPENDIX L

Soil organic matter content of five logging disturbance classes.

Depths, cm	General	Berm	Fire ring	Skid trail	Undisturbed
			Means, percent[a]		
0 to 3	12.7	12.3	8.0	9.2	19.9
3 to 6	6.9	10.4	7.8	7.6	7.5
6 to 9	5.3	10.9[b]	5.5	6.3	4.7
9 to 12	3.7	7.3	4.8	5.4	3.1
12 to 24	2.6	3.8	5.0	4.3	2.3
			Standard Deviations		
0 to 3	7.9	5.0	7.1	2.3	6.3
3 to 6	2.2	5.0	4.8	2.2	4.0
6 to 9	3.1	6.7	3.6	2.3	2.2
9 to 12	1.8	3.7	3.0	2.6	0.8
12 to 24	0.9	1.8	4.1	3.3	0.4

[a]Sample size is 12 except where indicated.

[b]Sample size is 11.

APPENDIX M

Soil organic material greater than 2 mm within logging disturbance classes.

General	Berm	Fire ring	Skid trail	Undisturbed
		Means, percent by weight[a]		
0.6	4.1	1.0	1.8	0.4
		Standard Deviations		
0.9	6.2	1.6	3.0	0.3

[a] Sample size is 10 for all means.

APPENDIX N

Soil particle size distribution of logging disturbance classes.

Class	General	Berm	Fire ring	Skid trail	Undisturbed
			Means, percent by weight[a]		
Sand[b]	39.4	39.8	42.1	41.8	42.1
Silt[c]	51.1	48.6	48.7	48.1	48.3
Clay[d]	9.5	11.7	9.2	10.1	9.6
			Standard Deviations		
Sand	4.3	4.9	2.6	3.7	2.3
Silt	3.7	3.3	2.6	2.8	2.0
Clay	2.0	4.1	1.7	2.0	1.4

a/ Samples taken at the 10.8 cm depth. Sample size is 10 for all means.

b/ 2.0 to 0.05 mm in diameter.

c/ 0.05 to 0.002 mm in diameter.

d/ $<$ 0.002 mm in diameter.

APPENDIX O

Soil mineral fragments greater than 2 mm within logging disturbance classes.

General	Berm	Fire ring	Skid trail	Undisturbed
		Means, percent by weight[a]		
22.3	17.0	15.8	17.3	15.3
		Standard Deviations		
9.9	9.8	6.2	3.1	7.0
		Sample Sizes		
10	10	9	9	10

[a]Samples taken at the 10.8 cm depth.

APPENDIX P

Areal extent of disturbance classes and slash on tractor-logged site, measured by line-intercept method.

Stand[a]	General	Berm	Fire ring	Skid trail	Undisturbed	'Light'[b] Slash	'Heavy'[c] Slash	Trees and Stumps
				Percent				
1	27.5	4.8	1.3	9.9	56.4	16.0	9.7	.7
2	23.5	8.9	3.0	10.6	54.1	8.1	4.6	.2
3	24.2	7.4	3.8	9.3	55.3	9.8	5.8	.7
4	16.5	10.0	0.0	11.4	62.1	18.6	7.9	1.4
$\bar{x}$	22.9	7.8	2.0	10.3	57.0	13.1	7.0	.8

[a] Stand area was 40 x 100 m.

[b] Suspended slash, such as felled sapling branches, that did not greatly obstruct plant growth.

[c] Slash lying on the ground that obstructed plant growth.

APPENDIX Q

Frequency of plant species on logging disturbance classes in the summer of 1980.

SPECIES	General	Berm	Fire ring	Skid trail	Undisturbed
GRAMINOIDS			Percent Frequency[a/]		
Calamagrostis rubescens	72	65	20	40	90
Carex geyeri	62	50	2	30	75
Carex rossii	52	58	20	55	12
Dactylis glomerata	30	40	18	82	2
Agropyron intermedium	22	42	2	80	--
Bromus marginatus	22	28	22	30	2
Phleum pratense	15	25	2	30	--
Stipa sp.	2	2	--	--	2
FORBS					
Gayophytum decipiens	75	68	42	75	10
Arnica cordifolia	60	65	8	25	65
Cirsium vulgare	42	30	38	60	10
Collinsia parviflora	55	52	5	25	12
Hieracium albertinum	20	32	18	12	65
Chryptantha sp.	25	18	15	12	5
Lupinus sp.	8	8	--	10	12

Appendix Q (continued)

SPECIES	General	Berm	Fire ring	Skid trail	Undisturbed
FORBS (continued)			Percent Frequency		
Polygonum douglasii	18	5	2	5	--
Fragaria virginiana	5	10	--	--	15
Unknown sp.	12	10	--	2	2
Silene menziesii	8	5	2	2	8
Unknown sp.	10	2	--	10	2
Viola sp.	8	2	--	--	5
Achillea millefolium	--	2	2	2	--
Epilobium sp.	--	--	--	5	--
Verbascum thapsus	--	2	2	--	--
Arenaria sp.	--	--	--	2	--
Linanthus sp.	2	--	--	--	--
Hieracium albiflorum	2	--	--	--	--
SHRUBS					
Ceanothus velutinus	20	18	25	20	2
Berberis repens	12	12	--	2	20
Spirea betulifolia	--	2	--	--	2

Appendix Q (continued)

SPECIES	General	Berm	Fire ring	Skid trail	Undisturbed
SHRUBS (continued)			Percent Frequency		
Pachistima myrsinites	2	--	--	--	--
Symphoricarpos albus	--	2	--	--	--

a/Percent of 40 plots for each disturbance class in which species were found.

APPENDIX R

Maximum soil surface temperatures in mid-summer 1980 for logging disturbance classes (°C).

Date	General	Berm	Fire ring	Skid trail	Undisturbed
7/1	39.4[a]	54.4	---	42.8[b]	44.4
7/2	41.1	51.7	---	42.2	38.3
7/3	30.0	31.1	---	28.3	26.7
7/6	41.1	42.8	41.7[b]	38.3	41.7
7/8	46.1	52.8	51.1	45.0	52.2
7/9	53.3	56.1	55.0	48.3	59.4
7/12	52.8	61.7	63.3	45.0	55.0
7/13	51.7	56.7	54.4	48.9	45.0
7/14	52.2	60.0	56.7	52.2	45.6
7/15	46.7	53.9[b]	51.7	43.9	38.3
7/16	56.1	60.0	55.6	51.7	46.1
7/17	60.0	62.8	53.9	50.6	50.6
7/19	57.8	58.3	56.1	55.0	61.1
7/21	62.8	64.4	60.6	56.1	52.8
7/24	65.0	68.1	62.8	60.0	62.2
7/25	63.9	63.3	62.8	61.7	58.3
7/26	61.7	62.2	61.7	57.8	56.7
7/27	63.9	64.4	62.2	60.0	61.7
7/28	65.0	63.9	62.8	60.6	61.7
7/29	53.9	53.9	54.4[b]	52.2	49.4
8/8	66.1[b]	67.8[b]	63.3	61.7[b]	68.1
8/9	60.0	56.1	60.6	60.6	60.0
Average	54.1	57.6	57.4	51.0	51.6

[a]Daily temperatures for each disturbance class are averaged from readings taken at three locations on site, except where noted.

[b]Temperature averaged from two readings.

APPENDIX S

Simple correlations of soil characteristics and herbaceous production on a tractor-logged site.

Variables[a]		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20
Bulk density:[b]	X1	1.00	.41	.46	-.10	-.17	-.26	-.85	-.71	.15	.34	-.10	-.34	.58	.50	.55	.68	-.07	.12	-.06	.04
Penetrometer resistance, 0 to 5 cm:	X2		1.00	.69	-.21	-.23	-.30	-.42	-.34	-.01	.00	-.10	.06	.20	.06	-.02	.54	.18	.29	.11	.32
Penetrometer resistance, 5 to 10 cm:	X3			1.00	-.30	-.33	-.26	-.33	-.22	.03	-.01	-.06	.04	.44	.33	.29	.56	.17	.30	.19	.20
1st infiltration run:	X4				1.00	.96	.34	.03	-.02	.29	.16	.01	-.21	-.01	-.06	-.01	-.17	-.12	-.15	-.13	.01
2nd infiltration run:	X5					1.00	.32	.07	-.02	.23	.14	.01	-.21	-.02	-.11	-.03	-.23	-.08	-.14	-.09	.10
Saturated hydraulic conductivity:[c]	X6						1.00	.53	.65	-.05	-.14	.02	.29	-.11	.07	-.06	-.14	-.09	-.10	-.11	.09
Walkley-Black organic matter:[d]	X7							1.00	.82	-.02	-.46	.11	.53	-.53	-.30	-.43	-.33	.13	-.02	.14	-.14
Organic matter > 2 mm:[d]	X8								1.00	-.29	-.44	.05	.63	-.29	-.24	-.27	-.23	-.03	-.14	-.04	-.05
Mineral fragments > 2 mm:[e]	X9									1.00	-.02	-.07	-.28	.03	.12	-.06	.09	.10	.21	.15	.13
Sand:[d]	X10										1.00	-.33	-.60	-.03	.10	-.24	.08	.12	-.22	.09	.06
Silt:[d]	X11											1.00	.10	.08	.22	.26	.00	-.01	.20	.02	-.48
Clay:[d]	X12												1.00	-.20	-.17	.09	.18	-.07	-.05	-.08	-.14
Moisture retained at -0.1 bars:[f]	X13													1.00	.58	.73	.32	-.16	.22	-.04	.12
Moisture retained at -0.3 bars:[g]	X14														1.00	.82	.43	-.05	.13	.12	.00
Moisture retained at -1.0 bars:[h]	X15															1.00	.53	-.32	.03	.01	.00
Moisture retained at -15.0 bars:[i]	X16																1.00	.13	.14	.12	-.05
Graminoid production:[j]	X17																	1.00	.02	.98	.06
Forb production:[j]	X18																		1.00	.15	.12
Total herbaceous production:[k]	X19																			1.00	.02
Belowground biomass:	X20																				1.00

Appendix S (continued): Footnotes

a/Observations made on 59 0.5 m^2 plots randomly located in a systematic fashion on five logging disturbance classes, except where subsamples are noted.

b/From soil cores taken from the 10.8 cm depth.

c/From 58 soil cores taken from the 3.2 cm depth.

d/From 50 soil cores taken form the 10.8 cm depth.

e/From 48 soil cores taken from the 10.8 cm depth.

f/From 58 soil cores taken from the 10.8 cm depth.

g/From 57 soil cores taken from the 10.8 cm depth.

h/From 47 soil cores taken from the 10.8 cm depth.

i/From 49 soil cores taken from the 10.8 cm depth.

j/50 plots used.

k/52 plots used.

APPENDIX T

Sample sizes required to estimate population means with a confidence interval of ± 20 percent at the 0.95 probability level for plant and soil characteristics of the study site, segregated by logging disturbance class. Stein's two-stage procedure is used: $n = t^2s^2/d^2$, where n = sample size, t = Student's "t" value at the 0.95 level, s^2 = the sample variance, and d = the half-width of the confidence interval.

Characteristic	General	Berm	Fire ring	Skid trail	Undisturbed
Total herbaceous production	54	103	633	42	25
Belowground biomass, 0 to 10 cm	87	105	199	68	45
Understory cover	33	39	182	19	22
Overstory canopy	48	34	23	41	36
Litter cover	31	72	517	57	1
Litter depth	103	209	103	53	30
Bulk density,					
3.2 cm	6	9	5	3	7
10.8 cm	3	8	4	7	1
18.4 cm	3	4	3	9	3
Soil strength,					
0 to 5 cm	20	63	49	15	7
5 to 10 cm	8	23	21	5	5
Soil infiltration,					
1st run	122	437	41	81	100
2nd	112	245	91	117	90
Saturated hydraulic conductivity, 3.2 cm	72	177	226	47	45

Appendix T (continued)

Characteristic	General	Berm	Fire ring	Skid trail	Undisturbed
Soil moisture content, 10.8 cm,					
- 0.1 bars	2	6	10	3	1
- 0.3	3	8	6	5	2
- 1.0	4	11	2	13	2
-15.0	3	2	5	5	2
Soil organic matter,					
0 to 3 cm	47	21	96	8	13
3 to 6	13	28	46	11	35
6 to 9	42	47	52	17	27
9 to 12	29	32	48	29	61
12 to 24	15	28	82	72	4
Soil organic matter > 2 mm, 10.8 cm	288	293	328	356	72
Soil particle size distribution, 10.8 cm,					
Sand (2.0 to 0.05 mm)	2	2	1	2	1
Silt (0.005 to 0.002 mm)	1	1	1	1	1
Clay (< 0.002 mm)	6	16	5	6	3
Soil mineral fragments > 2 mm, 10.8 cm	26	43	20	5	27