Impacts of Forest Harvesting and Regeneration on Forest Sites

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PREFACE

The terms of reference for this project required the preparation of:

1. a **selective** annotated bibliography of literature reporting on the impacts of forest harvesting and renewal on soil properties and site productivity, and pertinent to the development of site degradation assessment procedures and guidelines for interior British Columbia operations. This bibliography was to be organized into appropriate sub-sections and was not to include off-site impacts, and a short summary was to be written for each of the sub-sections;
2. a **selective** annotated bibliography of literature reviewing and comparing the costs and productivity of forest harvesting equipment used in interior British Columbia operations;
3. a **selective** annotated bibliography of literature assessing the economics of soil degradation;
4. an executive summary of the entire report;
5. an identification of research needs; and
6. as an appendix, as complete a list as possible of references from research on impacts of forest harvesting and renewal on soil properties and site productivity, on the economics of soil degradation, and on the operating costs and productivity of interior British Columbia forest harvesting equipment.

The authors used the following general criteria to select references for annotation:

- How relevant is the information to the topic?
- How relevant is the information to B. C. conditions and operating procedures?
- How useful is the information in aiding operational planning and decision-making?
- How specific and conclusive is the information presented?

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The assistance and support of Steve Chatwin and Gerry Still of the Research Branch of the British Columbia Ministry of Forests, Dick Smith of Pacific Forestry Centre (Forestry Canada), and Alex Sinclair of the Forest Engineering Research Institute of Canada (FERIC) are gratefully acknowledged.

The preparation of the annotations for the soils section was assisted substantially through contributions by Marty Kranabetter (Faculty of Forestry, University of British Columbia) and Bob Gadziola (Department of Soil Science, University of British Columbia).

Two reports, ''Costs and Productivities of Interior B. C. Forest Harvesting Equipment and Operations: An Annotated Bibliography,'' by N. G. Marshall of FERIC, and ''The Economics of Soil Degradation: An Annotated Bibliography,'' by W. A. White of Forestry Canada (Pacific Forestry Centre), comprise the basis for Sections II and III, respectively, of this bibliography.

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EXECUTIVE SUMMARY

Disturbance

All the available research information agrees that soil degradation associated with conventional forest harvesting is a major problem in British Columbia and elsewhere in the Pacific Northwest.

The extent of the harvesting-caused disturbance is influenced by certain soil conditions at the time of the activity: (e.g., soil strength, moisture content, degree of frost, and snow cover) and by particular characteristics of the activity, (e.g., frequency that machinery and logs pass over a given site location, and the forces [pressure and vibration] exerted by the machinery and logs on the soil). Yarding and the construction and use of haulroads, skidroads and landings have been shown to cause disturbance levels ranging from 6 to 87% of the harvested area, with deep disturbance (>25 cm depth) being recorded in the range of 0-60%. Ground-skidding systems account for 60% of the total volume harvested provincially and are responsible for the highest disturbance levels recorded.

Mineral soil exposure has been shown to range from 5% for some helicopter-or skyline-yarded areas to 70% for some tractor-yarded sites. Mineral soil exposure on ground-skidded sites generally ranges from 10 to 50% but can be reduced significantly (50%) by such practices as ensuring ample snow cover (>1 m) for skidding in winter and using planned, designated skid trails. Cable-yarding systems generally produce less mineral soil exposure, but can result in high levels of disturbance and exposure (56%).

Harvesting causes dramatic microclimatic effects in forest sites, especially in those that have been clearcut. These changes can pose severe limitations to forest regeneration, particularly because of lethal air and soil surface temperatures, frost-heaving, snow press, desiccation and wind damage.

Increases in surface soil layer (0-10 cm) bulk density have been reported in the range of 15 to 60% for skidroads and 25 to 88% for landings. These density increases generally do taper off with depth, but have often been observed to exist at depths of 30 cm or more. Although compaction effects may last for only 10 years or less at the soil surface, most evidence points to compaction effects persisting at all sampled depths for 30 years or more. Most compaction is produced during the first few passes of the equipment and logs. Subsequent passes have proportionately less effect, but may cause density levels which may alter root growth significantly. The compacting forces of operating machinery may cause soil puddling, the effects of which on soil productivity are similar to those caused by bulk density increases.

It appears that a soil bulk density value in the range of 1200-1400 kg m^3 is a critical threshold above which tree root growth will be reduced for the range of soil types and tree species in B. C. The evidence indicates that compaction-induced volume reductions over entire harvest areas in interior B. C. can be projected to average 10-15%.

Moving skidding machinery over the soil and pulling mechanical site preparation (MSP) equipment (passive and powered), and dramatically altering site characteristics through the use of prescribed fire can result in soil degradation and loss of site productivity if these treatments are improperly selected or poorly applied. Of the MSP treatments frequently used in the B.C. Interior, the one with the most potential for serious, detrimental effects is windrowing. Other treatments, such as blade scarification, V-blading, and bunching can have similar influences, but generally affect a much smaller portion of the treated area. Prescribed fire can result in the substantial loss of site nutrient capital during the burn or by erosion after the burn. If a burned site is subsequently treated (and re-treated) to control competing vegetation, nutrient cycling, retention and availability may well be impaired.

Almost all the research information available relates to the short-term effects of site preparation on seedling survival and growth. Very little information is available on long-term impacts of site preparation on soil properties and site productivity. There is some evidence, however, that various common MSP treatments can significantly harm soils and hinder tree growth. For example, whole treatment area reductions in productivity caused by windrowing, bunching, and blade scarification have been shown to amount to 20, 15 and 10%, respectively. While short-term prescribed-fire effects on tree growth are reasonably well-understood, long-term effects have been more difficult to identify. Evidence has shown that tree growth on burned sites may be better, poorer, or not different at all from that seen on unburned sites.

There are few literature reports of improved stocking and/or tree growth in areas of disturbed soils (e.g., skidroads), and only some undocumented, anecdotal field observations of similar situations. There is not enough information to produce general conclusions and specific guidelines as to specific site conditions which might be improved through disturbance.

Surface Erosion

Research has shown that forestry activities can accelerate the rate of surface erosion from 2 to 15 times. One study reported that surface erosion caused by building forest roads removed about 200 m^3 of soil per hectare of exposed slope. Studies have shown also that up to 85% of the total surface erosion can occur in the first year of disturbance and that >90% has usually occurred by the end of the second year. Stabilization measures such as seeding, planting, mulching, using tackifiers, and installing barriers have been demonstrated to reduce the amount of this erosion by up to 99%.

Harvesting, mechanical site preparation, slashburning, and plantation maintenance have reportedly promoted surface erosion by altering soil water regimes and decreasing soil strength through reductions in vegetative cover and root strength. Erosion losses can be enhanced also by the loss of soil structure and infiltration capacity following disturbance. As well, burning can create water-repellent layers on the soil surface which can then increase surface runoff.

Surface erosion, if allowed to develop to severe levels, can eliminate all vegetative growth for extended periods of time, resulting in a 100% conifer productivity loss for the rotation on the area directly affected.

Prevention of erosion problems through planning and on-site regulation of activities can alleviate much of the concern related to surface erosion, thus minimizing its economic and biophysical impacts.

Mass Movement

Root strength decreases rapidly after clearcutting, resulting in a period (likely 2 to 20 years in the Interior) during which marginally stable slopes are acutely vulnerable to mass movement until vegetative regeneration renews the stabilizing root network. Regenerating tree species, speed and nature of regeneration, and time to crown (and thus root) closure determine the length of this period of high slope failure hazard. Concern for accelerated degradation because of mass movement should be highest in the wetter biogeoclimatic subzones, such as the ICH, wetter SBS and ESSF, and BWBS.

Roads and road building are associated with the vast majority of landslides occurring on forested lands, and are usually related to drainage problems such as the saturation of fill slopes and the plugging of culverts. Roads have been reported to increase mass wasting rates from 25 to 34 times those observed on undisturbed forest slopes in coastal B. C.

Site Assessment Methods

Four main methods are available for surveying and assessing the level of soil disturbance on harvested blocks: aerial photography, point-intercept method, line-intercept method, and ground traverse method. Air photos can be used to estimate the areal extent of soil disturbance but cannot provide a direct estimate of severity of disturbance. The point-intercept, line-intercept, and ground traverse methods enable field measurements of areal extent and severity of disturbance. These methods can be used for quick surveys of disturbance as well as detailed assessments of degree of impact.

Sensitivity Rating Systems

Degradation sensitivity criteria can be used to derive standards for determining operational limits to disturbance. Standards, to be meaningful and practicable, must emphasize observable and measurable site characteristics which field personnel can easily use to monitor the impacts of the harvesting activities. Site sensitivity guidelines are presently being developed using biogeoclimatic and site variables from the zones and subzones in each Forest Region. Proposed B.C. standards for areal extent of acceptable levels of detrimental soil disturbance vary from 10 to 15% for sites of low to moderate degradation sensitivity and 3 to 8% for sites of high to extreme degradation sensitivity.

Rehabilitation

While restoration of site productivity may not be possible on severely degraded soils, rehabilitation techniques are available to reclaim some portion of the former productivity and to stabilize eroding soil surfaces. The long-term cost/benefits of rehabilitation are unknown.

Extension and Planning

Handbooks and guidelines should provide those people responsible for making harvesting and forest renewal prescriptions with a choice of forest management strategies which would not cause excessive site degradation and corresponding losses in productivity. For prescription development, forest managers should have access to an objective and efficient process for assessing site conditions and the relative sensitivity of a site to degradation. They should have access also to a selection of alternative, practical solutions for altering forest management practices to suit the different degrees of sensitivity observed. Various handbooks address three main aspects of harvesting and forest renewal: pre-harvest prescription development, prescription implementation and assessment, and mitigative or rehabilitative measures if soil degradation is anticipated or occurs.

For harvesting, there is evidence that the use of planned, designated skid trails can lead to substantially lower site compaction levels and lower site productivity losses, with no concomitant increases in logging costs or losses in machine productivity. Use of light flotation or smaller equipment, or logging on dry or frozen soils or over snow cover, can also reduce the extent of soil displacement and productivity losses. Selective road location, proper road construction, and responsive road maintenance and protection are all considered to be integral parts of responsible forest land management. Minimizing soil disturbance levels and changes to normal drainage patterns in a setting can also help protect the soil, forest, and off-site resources, and help provide economic opportunities in the future.

For site preparation, guidelines are available to aid foresters in evaluating site conditions, selecting treatment options, implementing treatments, monitoring treatment progress and success, and assessing post-treatment site conditions.

As well, there are guidelines for the use of rehabilitative procedures, measures and tools. However, it must be emphasized that reclamation or rehabilitation is more costly than planning and prevention and excessive soil degradation can lead to significant decreases in crop volume or even rotation-length losses of a commercial crop.

Costs and Productivity of Harvesting Equipment

Conventional ground-skidding methods appear to be more cost-effective than alternative ground-skidding systems or cable systems. Production costs for small crawler tractors and FMC's averaged about 10-20% more than those for conventional crawler tractors or rubber-tired skidders. Cable-yarding costs range between 65 and 160% higher than conventional costs.

Higher capital cost is a major component of increased production costs for cable yarders and FMC's, even though they may out-produce conventional harvesting equipment on a per-machine basis. Other organizational factors, such as the need to dedicate a loader to a cable yarder to keep landings clear, also contribute to higher costs.

Machine productivity (in cubic metres per man hour) can vary from 22.4 to 32.0 for conventional grapple-skidding equipment, 5.2 to 8.1 for small crawler tractors, 8.0 to 23.6 for FMC's, and 4.4 to 38.1 for cable yarders.

Economic Impacts

The economic analysis of soil degradation has received little attention to date because of the difficulty in obtaining appropriate data on the productivity impacts of site degradation, the values of off-site impacts and other pertinent information. The forest economics community has failed to spell out an appropriate approach to the analysis of the economics of soil degradation problems. This has resulted in a variety of models being proposed and utilized, but none has proven to be totally appropriate.

Few general conclusions can be derived from the literature on this topic. However, one of the more important and realistic is that better planning can result in better forest soils management. In the long-run, planning is more cost-effective and less expensive than rehabilitation efforts.

Research Needs

Being selective about specific research or information needs for soil degradation - site productivity relationships is difficult when so much is needed. A review of the literature and an analysis of recent discussions of soil degradation research needs indicate that the following eleven are the highest priority (these are simply listed, not ranked):

1. Establishment of extension programs dealing with soils interpretations and management, field planning, and block layout.
2. Assessment of site sensitivity and development of predictive tools to facilitate prescription development.
3. Development of simple, quick and reliable site degradation assessment and monitoring methods.
4. Installation of a greater variety of long-term research projects to examine soil and productivity changes caused by forest management.
5. Investigation of the effectiveness and costs of using planned and designated skid trails.
6. Examination of tree growth on and adjacent to landings and skid trails.
7. Rehabilitation, site-selection and decision-making guidelines.
8. Testing of rehabilitation strategies and techniques.
9. Development of a standardized approach for the economic analysis of soil degradation.
10. Determination of the economic impacts of soil degradation.
11. Assessment of operating costs and machine productivity for harvesting equipment appropriate to the range of interior site conditions.

CHAPTER I:
IMPACTS ON SOIL PROPERTIES AND SITE PRODUCTIVITY

1 SOIL DISTURBANCE

1.1 Summary

Soil disturbance is generally defined as any abrupt change in the physical, chemical, or biological properties of a soil. While it is an inevitable consequence of forest management activities, particularly harvesting and site preparation, the magnitude of the disturbance varies greatly with, for example, the method of logging used, type of site preparation treatment, site and terrain conditions, timing of activity, degree of pre-activity planning, and care taken by on-site personnel.

Soil disturbance can be categorized as one or more of the following: displacement, degree of exposure of mineral soil, compaction, puddling, erosion, mass wasting, nutrient depletion, micro-climatic changes, and site and slope hydrology changes (Froehlich 1988; Lewis 1988; Utzig and Walmsley 1988). The level of disturbance is considered to be severe or deep if it extends to a depth of 25 cm or more (Smith and Wass 1976). Slight disturbance generally signifies some impact to a depth of <25 cm. Disturbance levels are considered to be detrimental if site productivity is decreased; that is, if growth of vegetation, particularly the regenerating forest crop, is reduced.

The relationship between soil disturbance and crop establishment or growth is complicated by several factors (McColl 1983). Because the boundary between degradation and beneficial disturbance is not often clear, a good deal of subjective judgment is sometimes needed to infer site degradation (Ballard 1983a, 1988). These difficulties are a consequence of major limitations in our information base and our lack of long-term experience with particular sites and disturbance-productivity relationships. Because of the lack of research data and operational experience, every "rule" has a plethora of "exceptions" and, because of perceptions, such soils concerns can too often be viewed as constraints to operations as opposed to integral components of the resource planning and management phase. This makes the prediction of degradation potential very difficult. To predict degradation hazards adequately, the forest manager should understand the inherent site conditions, capabilities (potential responses), and sensitivity, as well as the objectives and impacts of the proposed activity (e.g., logging system or site preparation treatment).

1.1.1 Harvesting disturbance

The consensus in the literature is that soil degradation associated with conventional forest harvesting is a major problem in British Columbia and elsewhere (Agricultural Institute of Canada 1985; Ballard 1983a, 1988; Carr 1983, 1988; de Vries 1983; Froehlich 1988; Megahan 1988; Standing Senate Committee on Agriculture, Fisheries and Forestry 1984). The operation of logging equipment alters several soil physical properties, particularly structure, porosity, density, pore size distribution, aeration, water retention, infiltrability and hydraulic conductivity (Standish *et al*. 1988). Indirectly, the soil thermal regime can be affected by changes in soil bulk density, porosity and water retention. The extent of the disturbance is influenced by certain soil conditions at the time of the activity (e.g., soil strength, moisture content, degree of frost, and snow cover) and by particular characteristics of the activity (e.g., frequency that machinery and logs pass over a given site location, and the pressure and vibration forces exerted by the machinery and logs on the soil). Those activities involved in logging — construction and use of haulroads, skidroads and landings, and yarding — have been shown to cause disturbance levels ranging from 6 to 87% of the harvested area (summarized in Utzig and Walmsley 1988), with deep disturbance being recorded in the range of 0 - 60%. Ground-skidding systems account for 60% of the total volume harvested provincially and are responsible for the highest disturbance levels.

The extent of mineral soil exposure has been often used as an index of soil disturbance. Several disturbance surveys have been undertaken in B.C. (Bockheim *et al*. 1975; Krag *et al*. 1986; Schwab 1976, 1978; Schwab and Watt 1981; Smith and Wass 1976; Standish 1984; Thompson 1988), with mineral soil exposure ranging as high as 70% for some tractor-yarded areas. Values ranged from 10 - 47%, depending on slope primarily, for ground skidding in the Nelson Forest Region (Hammond 1984a). Such exposure can be reduced significantly (50%) by such practices as ensuring ample snow cover (>1 m) for skidding in winter (Hammond 1984a; Smith and Wass 1976). Cable yarding is not always the solution to decrease mineral soil exposure. Bockheim *et al.* (1975) recorded a level of 56% exposed mineral soil from one highly disturbed, high lead yarded site.

Related to degree of mineral exposure is soil displacement, the physical or mechanical movement of soil materials by logging equipment or moving logs. This includes both excavation and scalping of soils by way of cuts and scalps by blades, tracks, tires or logs. Also involved is the burying of surface soils adjacent to the areas of excavation or scalping. For ground-based skidding systems, the amount of soil displacement is regulated chiefly by the extent of cuts required for the network of skidroads. Adverse displacement problems can generally be minimized on slopes <30% (40% for flex-track skidders) because blading can be kept to a minimum. On steeper slopes, slope gradient, terrain complexity, skidroad pattern, spacing and gradient, equipment size, and operator care determine the extent of soil displacement.

Road construction in areas of complex, broken slopes or gullied terrain usually results in much greater soil displacement. Use of planned, designated skid trails and light flotation or smaller equipment, and by logging on dry or frozen soils or over snow can reduce the extent of soil displacement considerably (Lewis 1988; Utzig and Walmsley 1988).

Because of B.C.'s recent history of glaciation, its soils are shallow, with the bulk of the available nutrients located in the forest floor and upper mineral layer. The subsoils and parent materials have limited fertility and can have chemistry adverse to vegetative growth. If the nutrient-supplying layers are displaced, forest managers face the serious problems of nutrient deficiencies and exposure of unfavourable substrates on their sites. Exposed dense tills, dense silty and clayey glaciolacustrine deposits, dense clay-enriched horizons, sandy and gravelly glaciofluvial deposits, calcareous parent materials and saline parent materials do not provide the favourable physical, chemical and biological environment necessary for the establishment of commercial forest crops.

Harvesting causes dramatic microclimatic effects, particularly in clearcuts. These effects include changes to net radiation, to surface temperature maxima and minima, to the frost-free period (because of radiation cooling and cool air ponding), to soil and air temperatures, to soil moisture content, to windspeed and snow catch, and to ultraviolet light intensity (Hungerford 1979). These changes can pose severe limitations to forest regeneration, especially because of lethal soil surface temperatures, frost-heaving, snow press, desiccation and wind damage. The size, frequency and length of these microclimatic changes are primarily a function of the amount of canopy removed and the amount of exposed mineral soil.

Ground-based logging systems necessitate the construction of landings and skidroads, which are then subject to compaction. Landings can comprise 4-5% of a cutblock area, and skidroads 14-30+% (Carr and Mitchell 1987; Froehlich 1973; Hatchell *et al.* 1970; McLeod and Hoffman 1988; Schwab and Watt 1981; Smith and Wass 1976). The extent of compaction is determined by a combination of soil factors and the kind and magnitude of compactive forces applied. Key factors include the amount and type of pressure and vibration applied, the number of machine passes, the nature and thickness of the forest floor, soil structure, soil texture, soil density, and soil water content during the compacting activities (Adams and Froehlich 1981).

Increases in surface soil layer (0-10 cm) density have been reported in the range of 15 to 60% for skidroads (Carr and Mitchell 1987; Dickerson 1976; Smith and Wass 1985b; Steinbrenner and Gessel 1955b), and 25 to 88% for landings (Arnott *et al.* 1988; Carr 1987a; Perry 1964). These density increases do taper off with depth but have been observed frequently to exist at depths of 30 cm or more (Arnott *et al.* 1988; Carr 1987a; Froehlich 1979a; Gent *et al.* 1983; Haines *et al.* 1975; Wert and Thomas 1981). Related soil physical properties have also been seen to change: total and aeration porosity, air permeability, water infiltration and hydraulic conductivity (Carr and Mitchell 1987; Dickerson 1976; Gent *et al*. 1983; Hager and Sieghardt 1984; Hildebrand 1983; Steinbrenner and Gessel 1955b).

The duration of these density increases is an important consideration as well. Thorud and Frissel (1976) found that compaction longevity may be <10 years at the soil surface, but other authors have reported that compaction effects more often persist for a period of >30 years at all depths examined (Jakobsen 1983; Perry 1964; Wert and Thomas 1981). Most compaction is produced during the first few passes of the equipment and logs. Subsequent passes have proportionately less effect (Adams and Froehlich 1981; Hatchell *et al*. 1970) but may cause density levels which affect root growth significantly (Burger *et al*. 1985; Sidle and Drlica 1981).

When soil moisture content is high and buoyant forces prevent the compression of soil particles, soil structure and porosity can still be severely altered by the compacting forces exerted by the machinery. This effect is known as puddling, the result of which is often a platy structure and a loss of air or water exchange capability. Puddling effects on soil productivity are similar to those caused by compaction. Root channels and other pathways in the soil are important for water infiltration and movement (Chamberlin 1972; de Vries and Chow 1978). Compaction and puddling eliminate these channels, and thus reduce the rate of infiltration and subsurface flow (de Vries and Chow 1978). On some sites, however, water retention may be increased as soil density increases (Greacen and Sands 1980; Froehlich *et al*. 1980). Water retention may also increase in compacted, sandy soils, decrease in compacted loamy soils and either decrease or increase in compacted clay soils (Froehlich and McNabb 1984).

1.1.2 Site preparation disturbance

While site preparation treatment testing and impacts have received increasing research interest in recent years, there is still a great deal to learn about possible degradation effects of site preparation. The difficulty lies in the fact that mechanical site preparation, for example, is basically controlled disturbance - more specifically, controlled displacement. If the controlled displacement is effective and improves seedling survival and growth, this may mask any possible soil degradation which may have occurred. Such degradation effects may show up in later years as the stand develops, or in subsequent rotations.

The two major types of site preparation treatments used in B.C. are mechanical site preparation (MSP) and prescribed burning. The general objectives for both tools are similar: reduction or alteration in slash loading; removal, reduction or *in situ* disturbance of surface organic layers; increase in nutrient availability; control of competing vegetation; and improvement in planting site microclimate, the number of plantable spots, and planter access. All of these objectives involve the direct or indirect manipulation of the soil organic matter and, thus, the fertility of the site and soil physical properties. In other words, these are attempts to manage the soil.

Because we have a limited understanding of the functioning of forest soils in B.C., we cannot accurately determine whether our soil management strategies are actually maintaining or enhancing soil productivity in the context of an ecological time frame (e.g., successional stage or rotation). Site preparation is geared to the re-establishment of a commercial crop and, to that end, has been relatively successfully applied in B.C.

Moving machinery and pulling implements (passive and powered) over the soil, or dramatically altering site characteristics through the use of prescribed fire, can result in soil degradation and loss of site productivity if these treatments are poorly selected or improperly applied. Several logistical factors can interfere with the successful application of these treatments: weather (too wet, too dry, too windy); poor equipment availability; lack of adequately trained personnel; or equipment failure. Thus, the use of MSP equipment may lead to greater soil density and increased erosion hazard.

Of the MSP treatments frequently used in the B.C. Interior, the one with the most potential for serious, detrimental effects is windrowing (Revel 1976). Repeated machine travel, extensive scalping and compaction, site organic matter concentrated on a small amount of the treated area, loss of organic matter and nutrients through combustion and volatilization, high intensity fires, and burning of the mineral soils underlying the rows are degradation hazards related to windrowing. Other treatments such as blade scarification, V-blading and bunching can have similar types of effects, but generally affect a much smaller portion of the treated area.

Other options in MSP (e.g., drag or patch scarification) substantially reduce the size and continuity of disturbed areas and provide a much better growing environment for the commercial crop (Dobbs and McMinn 1977; McMinn 1974, 1984b, 1986). With little information on the long-term efficacy of these treatments in terms of encouraging tree growth and providing vegetation control, and on the physico-chemical and biological responses of the treated soils, we have difficulty knowing if site productivity has been impaired.

No site preparation treatment has been studied more in B.C. and the Pacific Northwest or has generated more volatile debate than prescribed fire. Much of the research points to the success of prescribed fire in the establishment of new plantations on sites which can be burned, and of species which can pioneer in the resultant environment. A wealth of operational experience has been accumulated in the province, and operational guidelines are available for planning, implementing and monitoring prescribed burns.

Attaining the short-term objectives of the burn may, however, be costly in the long term. Prescribed fire can result in the substantial loss of site nutrient capital during the burn or by erosion after the burn. If a burned site is subsequently treated (and re-treated) to control competing vegetation, then nutrient cycling, retention and availability may well be impaired. It is not yet known with any certainty how this will affect site productivity.

1.2 Annotated Literature

Amaranthus M. and D.H. McNabb. 1983. Bare soil exposure following logging and prescribed burning in southwest Oregon. *In* New Forests for a Changing World. Proc. 1983 SAF National Convention, pp. 234-237.

This study examined the bare soil exposure occurring after broadcast burning and skyline harvesting in southwest Oregon. Prior to harvesting, duff depths averaged less than 2 cm and bare soil exposure averaged 1% or less. Bare soil exposure after harvesting ranged between 5.1 and 14.0%, but increased to 18.2 and 74.6% after broadcast burning. Bare soil exposure after broadcast burning was significantly related to the amount of duff originally present on the site.

Ballard, T. M. 1984a. Forest soils considerations in site preparation. SISCO Summer Workshop, Fernie, B. C. Unpubl. paper. 12 p.

The more important soil considerations related to site preparation are effects on soil temperature, aeration, water regime, frost-heave susceptibility, and nutrient availability. Some useful generalizations include: 1) Growing-season temperatures within the root zone are usually increased, with benefits to tree seedlings, where mechanical site preparation or slashburning is carried out; 2) Brush reduction may result in increased soil surface temperatures. Where lethal temperatures are a potential problem, mechanical site preparation resulting in more mineral material at the surface will be beneficial; 3) Seedling temperature regime, and/or seedling root zone drainage can be benefited if planting takes advantage of micro-relief aspect. Therefore, site preparation which creates some micro-relief (e.g., by spot scalping, mounding, or ploughing) may be particularly useful on some sites; 4) Soil aeration (and seedling growth) may be impaired by soil structure degradation, which can result from mechanical site preparation. Degradation is most serious if machinery is used when the soil is wet. The severity of this problem also varies with the equipment used and the soil texture and structure; 5) Exposure of silty or loamy mineral soils at the surface may lead to frost-heaving of seedlings, particularly if subsurface soil is moist; 6) Organic matter removal amounts to nutrient removal. Small scalps are, therefore, theoretically preferable to large scalps; 7) Preliminary research results indicate that mounding provides a good nutritional environment for planted seedlings; and 8) Burning has resulted in deficiencies of nitrogen, iron and copper in planted white spruce in the central Interior.

Barker, J.E. 1982. The effects of slash burning on nutrient concentrations of higher elevation soils at Jordan River. Western Forest Products. Final Report, Project WFP 25-003. 13 p.

The effect of slashburning on nutrient concentrations of high elevation sites was examined. The sites were located near the crest of the ridge between Loss Creek and the San Juan Valley. The area had slopes of 20-70% and the soils were eluviated dystric brunisols. Slashburning had a minimal effect on the nutrient budget for most of the area.

Bockheim, J.G., T.M. Ballard, and R.P. Willington. 1975. Soil disturbance associated with timber harvesting in southwestern British Columbia. Can. J. For. Res. 5(2): 285-290.

Soil disturbance associated with timber harvesting was evaluated in localities in southwestern British Columbia, along transects located away from main haulroads and associated sidecast soil material. Small skid trails and associated sidecast material were included in the evaluation. Of the several disturbance indices evaluated, the percentage of area occupied by exposed mineral soil (EMS) appears to be most useful. For 13 high-lead logged sites, EMS averaged 29% and ranged from 5 to 56%. Low EMS (9%) was associated with a high-lead site logged over snow, and high EMS with steep slopes (>70%) and shale-rich soils. Less disturbance occurred on soils derived from granitic parent materials. On two tractor-logged sites with 25-60% slopes, EMS was 71 and 68%, respectively. On a helicopter-logged site, EMS was only 5%.

Burger, J.A., J.V. Perumpral, R.E. Kreh, J.L. Torbert, and S. Minaei. 1985. Impact of tracked and rubber-tired tractors on a forest soil. Trans. ASAE 28 (2): 369-373.

This study was a comparison of compaction brought on by two types of equipment, a rubber-tired skidder (mean ground pressure of 230 kPa) and a crawler (mean ground pressure of 60 kPa). The sandy clay loam soil increased in density from 1.3 g/cm^3 to 1.5 g/cm^3 after the first three passes, and then showed little change. No differences were found between machine types. The level of soil moisture significantly affected the degree to which soil was compacted. At 18% moisture, the overall increase in soil density was 0.10 g/cm^3; at 21% moisture, the increase was 0.18 g/cm^3. Soil density and porosity changed proportionally with the square root of the number of passes over the same area.

Butt, G. 1987. Effects of skidder compaction on tree productivity. MacMillan Bloedel Limited, Nanaimo, B. C. Unpubl. Report. 62 p.

The results of this study indicated that skidder logging causes significant and lasting soil compaction (at least 25 years) on the sites studied. Increases in bulk density ranged from 11 to 80% (mean of 52%) in the surface (10 - 20 cm) layer and from 12 to 56% (mean 34%) in subsurface (10 - 20 cm) layers. This study also concluded that skidder logging on well-drained soils (medium to moderately coarse-textured, ranging from clay loams to sandy loams) on southeastern Vancouver Island were not deleterious to stand productivity.

Growth performance of Douglas-fir trees growing on six compacted but well-drained skid trail soils was compared to that of trees growing in undisturbed soils. Skid trail trees, both planted and naturally established, showed no consistent inferiority to off-skidtrail trees in height and diameter increment. Trees planted on skid trails showed inferior growth performance to those planted away from skid trails in 7 out of 23 plots, superior performance in 2 plots, and no significant difference in the remaining 14 plots. Trees planted on skid trails were also more frequently subject to browsing by deer or to vehicular damage.

Trees growing within 3 m of the edge of skid trails showed superior height and/or diameter growth, compared to those growing further away from skid trails, in 8 out of 23 plots. In 14 of the remaining 15 plots, no significant differences were found. In only one plot was height growth superior in control trees compared to flank trees. The flanks also exhibited greater stand volumes than did controls in 9 out of 13 plots subjected to volume calculations (although in only 2 of these plots were the differences significant). The difference in volume in all nine cases compensated for loss of volume on skid trails. When these volumes are pro-rated over a unit area, all 9 cases indicate increasing total volume with increasing skid trail area. This should not be interpreted as an argument for careless skidder logging, since there is still no basis for predicting on which sites total volume will be increased.

Dickerson, B.P. 1976. Soil compaction after tree-length skidding in northern Mississippi. Soil Sci. Soc. Am. J. 40: 965-966.

This study of skidding compaction was done on a loamy sand to a silty clay loam soil in the Oxford area of northern Mississippi. After 20 runs with a rubber-tired skidder, bulk densities of wheel-rutted soils increased an average of 20% to 1.55 g/cm^3; the increase was 10% for the soils between the ruts which were compacted by the movement of logs. Macropores were reduced 68% for wheel-rutted soils and 38% for log-disturbed soils; micropore space of both increased about 7%. Percolation rates decreased initially but recovered gradually. Wheel-rutted soils required about 12 years and log-disturbed soils about 8 years to return to pre-logging density levels. To assist the prompt restoration of desirable soil properties and to encourage seedling survival and growth, such practices as disking are necessary following tree-length skidding operations.

Donnelly J.R. and J.B. Shane 1986. Forest ecosystem responses to artificially induced soil compaction. I. Soil physical properties and tree diameter growth. Can. J. For. Res. 16: 750-754.

Soil and vegetation responses to artificially imposed surface compaction and the effects of bark mulch on these responses were monitored for a 5-year period within an oak forest growing on a loamy sand in northwestern Vermont. Soil bulk density, measured with a single probe moisture density instrument, increased with depth. Densities averaged 0.94, 1.17, 1.22, and 1.24 g/cm^3 in the 0-5, 10-15, and 15-20 cm depth zones, respectively. The compacted soil was found to have higher soil moisture than the control plots, ranging from 27 to 32% compared to the control range of 16 to 26% (percent by volume). Soil infiltration capacity was 3-5 times greater in the control plots over the compacted plots. Soil penetration resistance and soil temperature also increased following compaction. Application of bark mulch prior to compaction tended to reduce compaction effects. Post-compaction additions of bark mulch did not result in noticeable amelioration of compaction-induced changes 2 years after application.

Dyrness, C.T. 1965. Soil surface condition following tractor and high-lead logging in the Oregon Cascades. J. Forestry 63: 272-275.

The surface soil conditions and bulk density (0-5 cm depth) were investigated after tractor and high-lead logging over a variety of soils. High-lead and tractor logging resulted in the same proportion of the area being slightly disturbed or deeply disturbed (23% and 9%, respectively). However, the tractor-logged area had about 3 times more area within the compacted class (27% versus 9%). Soil bulk density values for the deeply disturbed and compacted classes were higher than for the undisturbed or slightly disturbed classes.

Dyrness, C.T. 1972. Soil surface conditions following balloon logging. USDA For. Serv., Pac. NW For. Range Exp. Sta. Res. Note PNW-182. 7 p.

Five areas at Deception Creek in the Willamette National Forest were logged by balloon. The soil was a regosol having a silty loam texture. The proportion of the area in the deeply disturbed and compacted classes was 4.3%, which is very low compared to other logging methods (tractor, high-lead and skyline). Only 15.8% of the surface area was slightly disturbed which is lower than for other logging methods. On areas logged by high-lead, 57% of the area was undisturbed compared to 78% for balloon logging. Slight disturbance ranged from 21 to 26% for tractor, high-lead, and skyline logging, and was 16% for balloon logging. The amount of bare area exposure after logging was 14.1% for high-lead, 12.1% for skyline, and 6.0% for balloon.

Dyrness, C.T. 1976. Effect of wildfire on soil wettability in the high Cascades of Oregon. USDA For. Serv., Pac. NW For. Range Exp. Sta. Res. Paper PNW-202. 18 p.

Soil wettability and trends in recovery of vegetation were studied for 6 years after a major fire in 1967 that affected 3119 ha of lodgepole pine forest. Wettability of the sandy soils was evaluated by determinations of the liquid/solid content and the infiltration rate. Burning increased the water repellancy of the soil at depths of 2.5-22.9 cm, and this effect persisted for 5 years. Infiltration rates recovered more rapidly — as did vegetation — on lightly-burned than on heavily burned soils.

Entry, J.A., N.M. Stark, and H. Lowenstein. 1986. Effect of timber harvesting on microbial biomass fluxes in a northern Rocky Mountain forest soil. Can. J. For.Res. 16: 1076-1081.

Microorganisms of a forest soil are largely responsible for its relative quality within limitations of climate, soil and geology. They thus play a major role in forest soil productivity. Changes in soil microbial activity brought about by timber harvesting would be expected to persist as long as changes in the abiotic variables and easily decomposable organic matter that contribute to microbial metabolism persisted. When residue is left on site after clearcutting, microbial activity can be expected to increase; when residue is removed or the site is broadcast-burned, microbial activity can be expected to decrease. Future tree growth after harvest will ultimately depend on mineralization of those nutrients from organic matter by soil microorganisms. Treatments which remove a large portion of available nutrients from the site, while reducing microbial activity, could eventually limit stand development.

Froehlich, H.A. 1978a. Soil compaction from low ground-pressure, torsion-suspension logging vehicles on three forest soils. Oreg. State Univ., For. Res. Lab., Corvallis, OR. Res. Paper 36. 12 p.

Soil compaction and surface disturbance from logging vehicles were examined on three sites having different soils. The sites were located at Mt. Hood in the Cascades, at Umpqua in western Oregon, and at Malheur in eastern Oregon. The Mt. Hood site was a sandy loam with a 5-20 cm thick litter layer. The Umpqua site had a sandy clay loam with a 13-23 cm thick litter layer. The site in eastern Oregon was a sandy loam with a <1 cm thick litter layer. Soil density increased at 5-10 cm depths during the first 20 trips. Density continued to increase slowly in the amount and depth with the number of trips, especially as the litter layer was removed. In western Oregon with slopes under 30%, skidding disturbed 12-15% of the surface area. Skidding heavily disturbed 2-3% of the surface area. In eastern Oregon, 20 trips exposed mineral soil on 20% of the surface area. As slope increased, fewer number of trips disturbed more surface soil.

Froehlich, H.A. 1979b. The effect of soil compaction by logging on forest productivity. Report to BLM, Contract No. 53500-CT4-5(N). Oreg. State Univ., Forest Engineering Dep., Corvallis, OR. 45 p.

A study was undertaken on three forest sites in western Oregon to determine the effect of soil compaction on seedling growth. On the Mollala plot, the small crawler tractor produced a 9 and 14% increase in soil density with 6 and 10 trips, respectively. On the Dunn Forest plot, the difference in soil density was not significantly different between 6 and 10 trips, where it averaged 9.7% higher than that in the undisturbed soil. Height growth of the seedlings was affected by increasing soil density. Six- and 10-trip trails on the Dunn Forest plot had 8.5 and 13.9% less height growth than the 0 and 1 trip plots. On the Molalla plot the 6- and 10-trip trails produced seedlings with 11 and 21% less height growth over the 4 years of observation.

Roughly, each percent increase in soil density is associated with a 1.3% decrease in height. On the Ponderosa pine site, the average density of the heavily used skid trails was close to 1.24 g/cm^3 and this is associated with a 29% reduction in height growth. Roughly, each percent increase in density is associated with about 0.67% decrease in height growth. Volume growth is affected to a greater extent than is height growth. A 12% increase in soil density above 0.84 g/cm^3 is associated with a 26% decrease in stem volume. Trees planted on heavily used skid trails averaged about one-third the volume of those growing on non- to lightly compacted trails.

Froehlich, H.A. and E.R. Berglund. 1979. The effect of soil compaction during thinning on the growth of residual trees. *In* Report to BLM, Contract No. 53500-CT4-5(N). Oreg. State Univ., Forest Engineering Dep., Corvallis, OR. 19 p.

This study examined the effects of tracked and wheeled skidders on soil density and the growth of residual trees in a Douglas-fir stand in Oregon, thinned 5-15 years earlier. Compaction of the loamy soils had occurred from the use of thinning equipment, resulting in 60% of the trees on the heavily compacted sites (>10% increase in bulk density, >40% of the area compacted) having lower growth rates after thinning (30% reduction). Fourteen percent of the trees in the moderate compaction class (major impact is more than 2 m from the stem) had lower growth rates (14% reduction) after thinning. Four percent of the lightly disturbed trees had reduced growth rates.

Froehlich, H.A., D.E. Aulerich, and R. Curtis. 1981. Designing skid trail systems to reduce soil impacts from tractive logging machines. Oregon State Univ., School For., Corvallis, OR. Res. Paper 44. 15 p.

The effect of planned skidding trails versus the conventional system (selection by loggers) was examined in 35- to 40-year-old Douglas-fir stands. The planned system resulted in less damage to residual trees and reduced the area of compacted soil by at least two-thirds.

Froehlich, H.A., J. Azevedo, P. Cafferata, and D. Lysne. 1980. Predicting soil compaction on forested land. Forest Engineering Dep., Oreg. State Univ., Corvallis, OR. Unpubl. Proj. Summary. 3 p.

This study examined the influence of simulated log skidding on compaction of four different forest soils types (sandy loam, gravelly sandy loam, gravelly clay loam, loam) using three different logging vehicles (rubber-tired skidder, crawler tractor, and torsion-suspension vehicle). Soil densities increased rapidly during the first few passes: 6 trips with any machine produced about 60% of the final change after 20 trips. For these 4 soils, increase in soil density of the surface 20 cm after 20 passes averaged 16% with the crawler tractor, 11% for the rubber-tired skidder, and 9% for the torsion-suspension vehicle. The change in soil density after 20 trips was accompanied by a measured 43% reduction in soil macroporosity, as well as a 78% reduction in infiltration capacity by the crawler tractor and 67% by the other two machines.

Froehlich, H.A., D.W.R. Miles, and R.W. Robbins. 1985. Soil bulk density recovery on compacted skid trails in central Idaho. Soil Sci. Soc. Am. J. 49: 1015-1017.

In west-central Idaho, the bulk densities of soil in major skid trails were compared with those of adjacent undisturbed soil to determine rates of recovery. Two soil types were examined, a granitic material, and a volcanic material, which had been logged 1 to 23 years previously. For the granitic site, bulk density increased over undisturbed sites at 5.1, 15.2 and 30.5 cm depths by 25.9, 24.2, and 22.7%, respectively, after 5 years. After 25 years, the recovery was not complete at lower depths, with density differences of -3.0, 12.9 and 7.9% at the three depths. The volcanic soil showed higher differences in compaction, with bulk densities at the 5.1, 15.2 and 30.5 cm depths being 44.5, 46.2 and 43.3% higher, respectively. After 25 years, the density differences had decreased to 15.4, 26.1, and 4.8%. The recovery rates of the two soils were not significantly different.

Garrison, G. A. and R. S. Rummell. 1951. First year effects of logging on ponderosa pine forest range lands of Oregon and Washington. J. Forestry 49: 708-713.

The effect of logging on soil disturbance was examined in some loam soils in eastern Oregon and Washington. Tractor logging resulted in more than 50% of the area having deep soil disturbance in excess of 2.5 cm, and up to 61 cm. Cable logging showed more total disturbance, but the intensity of disturbance was much less severe. Only 1.9% of the ground surface for cable logging compared to 15% for tractor logging had deep soil disturbance. Plots having slopes of 40% or greater averaged 2.8 times more deep soil disturbance than plots of less than 40%.

Gent, J.A., R. Ballard, and A.E. Hassan. 1983. The impact of harvesting and site preparation on physical properties of Lower Coastal Plain soils. Soil Sci. Am. J. 47: 595-598.

Following tractor logging of a 25-year-old loblolly pine stand on a fine, loamy soil in North Carolina, comparisons were made between bulk density, aeration porosity, and saturated hydraulic conductivity values taken before and after logging. Harvesting increased bulk density and decreased aeration porosity in all sampled areas, with changes significant to 30 cm in depth on skid tracks and to 15 cm on the harvest portion. Hydraulic conductivity decreased in the top 8 cm of skid tracks. The bulk density in the skid trail plots exceeded 1.4 g/cc, while the aeration porosity was lower than 10%.

Hammond, H. L. 1984b. Soil disturbance levels in ground skidded, clearcuts in southeastern British Columbia. *In* Proc. 1983 SAF Nat. Conv. Portland, OR. pp. 228-232.

Soil disturbance was estimated in ground-skidded, clearcut areas in southeastern British Columbia. Three types of logging equipment were evaluated: small crawler tractors, rubber-tired skidders, and low-ground-pressure tracked skidders. Soil disturbance on haulroads, landings, and skid trails increased with slope gradient and terrain complexity. When roads followed the contour of the terrain (parallel to the direction of ridges and gullies), total disturbance was usually low. Sites logged on snowpacks of greater than 1 m showed approximatley 50% less soil disturbance and 80% less soil compaction than sites logged without such protection. The use of rubber-tired skidders on slopes less than 20%, and in combination with other machines on slopes greater than 20%, resulted in 20-30% greater disturbance than did the use of crawler tractors. Small crawler tractors caused 20-30% less soil disturbance than medium-sized crawler tractors. A sensitivity rating system was developed for evaluating a site's suitability for ground skidding, to reduce the levels of soil disturbance.

Harvey, A.E., M.F. Jurgenson, M.J. Larsen and J.A. Schlieter. 1986. Distribution of active ectomycorrhizal short roots in forest soils of the Inland Northwest: effects of site and disturbance. USDA For. Serv., Intermount. For. Range Exp. Sta. Res. Paper INT-374. 8 p.

Harvesting and site preparation resulted in low to extremely low organic matter reserves, reflecting mixing, transport, and loss of the forest floor. In the site types studied, approximately 75% of the active ectomycorrhizal short roots occurred in the organic materials accumulated in the first 4 cm of the forest floor. Depletion of soil organic matter reserves can reduce the ability of the soil to support ectomycorrhizal development and subsequent host (conifer seedling) growth. The active ectomycorrhizal short roots are those roots primarily responsible for the uptake of moisture and nutrients required for conifer survival and growth. Thus, the surface organic layers are important for supporting this critical feeder root development and activity. Management activities (harvesting and site preparation), which are likely to cause depletions in the soil organic matter content, should be undertaken in such a way as to minimize the loss or disruption of surface soil horizons.

Haupt, H.F. 1960. Variation in areal disturbance produced by harvesting methods in ponderosa pine. J. Forestry 58: 634- 639.

In an area of the Boise Basin Experiment Forest in Idaho, the variation in soil disturbance produced by two harvesting methods, selection and group harvest, was examined. The sites were composed of steep slopes, having loose sandy soil derived from granite. The dominant forests were old-growth ponderosa pine. The degree of surface bareness was determined arbitrarily by classifying the areal disturbance as showing exposure of more or less than 50% of mineral soil. It was found that the area of soil that is bared by harvesting is closely related to the number and volume of trees removed. As the intensity of timber cut by single and group selection increased from 3885 to 16835 trees per square kilometer, the area of soil bared increased from 4.5 to 117.8 ha and from 4.5 to 13.1 ha/km2, respectively. Greater tree dispersion and less repeated usage of skid trails and haulroads accounted for more bared soil in single tree harvesting. In group selection, tractor size showed no significant difference in areal disturbance. Group selection resulted in less soil disturbance than single tree selection. When large D-8 type tractors were used, disturbance from skidding was almost twice that of road disturbance (5.3 ha versus 3.0 ha/km^2). For the small D-4 type tractors, the effect was reversed (2.7 ha versus 5.2 ha/km^2).

Heilman, P. 1981. Root penetration of Douglas-fir seedlings into compacted soils. For. Sci. 47: 660-666.

Laboratory experiments were conducted to examine the relationship of soil compaction to root growth in a sandy loam and a loam soil. Root penetration decreased as bulk density increased from 1.33 to 1.77 g/cm^3.

Hungerford, R. D. 1979. Microenvironmental response to harvesting and residue management. *In* Symp. on Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests. USDA For. Serv., Intermount. For. Range Exp. Sta., Ogden, UT. Gen. Tech. Rep INT-90, pp. 37-73.

This paper discusses the usefulness of the concept of energy balance to analyze the environmental changes and to predict biological responses that follow timber harvesting and residue management. The physical properties of the surface have a large effect on the surface environment. Surface conditions, such as radiation load and temperature, reached lethal levels following harvesting on several sites. Harvesting also aggravates and creates frost pockets that severely limit seedling establishment. Some predictive models are discussed that aid in predicting environmental conditions and relate to biological implications. Methods of using residue manipulation to alter the microenvironment are suggested.

Kraemer, J. F. and R. K. Hermann. 1979. Broadcast burning: 25-year effects on forest soils in the western flanks of the Cascade Mountains. For. Sci. 25 (3): 427-439.

To determine the long-term effects of broadcast burning on the physical and chemical properties of forest soils, soil samples were collected from paired burned and unburned plots established between 1947 and 1953 after clearcutting in the western Cascade Mountains of Oregon and Washington. Soils were analyzed for organic matter content, total nitrogen, phosphorus, potassium and calcium, as well as for permeability and wettability. Results failed to show statistically significant differences between properties of burned and unburned soils, suggesting that broadcast burning does not have a lasting effect on chemical and physical properties.

Krag, R.K. and S.R. Webb. 1987. Cariboo Lake logging trials: production, performance, and costs of rubber-tired skidder, small crawler tractor, and cable yarding systems on steep slopes in the central interior of British Columbia. FERIC, Vancouver, B.C. Tech. Rep. TR-76. 48 p.

In the Cariboo Forest Region, the effect of three harvesting systems on soil disturbance was studied. The three systems were a small crawler tractor, a cable yarding operation, and a rubber-tired skidder operation. Slopes ranged from 0 to 80%, and the soils were sandy loams and loams. Assuming that each system required the same amount of logging roads and landings, total soil disturbance was 22.4% (summer) and 23.8% (winter) for the small crawler tractors, 10% (summer) and 7.6% (winter) for the cable system, and 34.1% (summer) for the conventional system (rubber-tired skidders). However, cable systems require more roads and landing areas per hectare than conventional systems (as much as 50% more). For the small crawler-tractor system, 61% of the samples from summer trails had bulk densities 15% greater than adjacent undisturbed trails, compared to 32% of the samples from winter trails.

Krag, R.K., K. Higginbotham, and R. Rothwell. 1986. Logging and soil disturbance in southeast British Columbia. Can. J. For. Res. 16: 1345-1354.

The purpose of this study was to document and to analyze extent, type, and degree of soil disturbance on ground-skidded and cable-yarded cutovers. The primary hypothesis was that ground skidding on steep, high elevation sites generates more soil disturbance than cable yarding. Thirty-one cutovers were surveyed in the Nelson Forest Region: 25 logged by ground skidding and 6 by cable yarding. Three replications were obtained for each season — slope class on ground-skidded sites. Cable-logged areas were also replicated three times, but only for season. Elevation of the cutovers ranged from 910 to 1970 m with an average of 1360 m. Slope steepness on cutovers ranged from 5 to 74%. Soil disturbance was significantly greater on ground-skidded than on cable-yarded cutovers, averaging 40-45% vs. 22-30%, respectively, regardless of season. Differences in soil disturbance between logging methods were small and not significant. Average soil disturbances for summer cable yarding and ground skidding were 30 and 45%, respectively, compared with 22 and 40% for winter operations. Analysis of soil disturbance by source revealed skidroads as the major cause of disturbance on ground-skidded cutovers, regardless of season. The primary source of disturbance on cable-yarded areas was yarding in the summer and haulroads in the winter. Ground skidding also caused more deep to very deep disturbance, averaging 30% in winter and 35% in summer compared with 18 and 14% on cable-yarded sites. For both methods, deep and very deep disturbance were most common, accounting for 75-80% of total disturbance.

Kuennen, L., G. Edson, and T.V. Tolle. 1979. Soil compaction due to timber harvest activities. USDA For. Serv., North. Region. Soil Air & Water Notes 79-3. 6 p.

Soil bulk densities, macropore porosities, and infiltration rates were measured on several logged sites on glacial till soils with surface layers of volcanic ash-influenced loess. Bulk density measurements, calculated by the saran-clod method, showed densities of 1.15, 1.23, and 1.74 g/cm^3 at 10, 20 and 40 cm depths, respectively. This represents an increase of 19, 15 and 5% over the undisturbed samples. There was an approximate 40% reduction in initial infiltration rates on disturbed sites compared to those on undisturbed sites.

Laing, L.E. and S.W. Howes. 1988. Detrimental soil compaction resulting from a feller buncher and rubber-tired skidder timber harvest operation: a case study. *In* Degradation of forested lands - forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56, pp. 191-195.

A monitoring project was conducted in 1983 on a timber sale unit on the Colville National Forest to quantify the degree and extent of detrimental soil disturbance following clearcut, whole-tree harvest with a feller buncher and conventional rubber-tired skidder. The study area was located in northeastern Washington, on a nearly flat (0-20% slope) glacial outwash terrace, with the soil a sandy loam. Logging took place in the late spring when the soil moisture was at or near field capacity. Soil disturbance occurred over 41.8% of the area logged. Most of this disturbance (98%) was detrimental compaction, indicated by a bulk density increase of 20% or more over the pre-disturbance level at a soil depth of 10-15 cm. The mean bulk density increase of the detrimentally compacted samples was 36%. Productivity losses of 15% of the total potential yield are projected, as a result of detrimental soil compaction during the next rotation if effective remedial measures are not implemented. Approximately 3.5% of the total potential yield of the unit would be lost to the dedication of land to skid trails and landings.

McLeod, A.J. 1988a. A pilot study of soil compaction on skid trails and landings in the Prince George Forest Region. *In* Degradation of forested lands - forest soils at risk. J. D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56, pp. 275-280.

This was a preliminary study of soil compaction on skid trails and landings in the Prince George Forest Region using a single-probe nuclear densiometer to measure soil density. The soils in the various cutblocks ranged from silt to silt loam. The general conclusion is that all landings are compacted to unacceptable levels for future crop production (B.D. >1200 kg/m^3), although summer landings were more compacted than winter landings. Also, summer skid trails were compacted to unacceptable densities, while winter skid trails (for the most part) were not.

McLeod, A. and E. Hoffman. 1988. A pilot study of the amount of soil disturbance on selected cutovers in the Prince George Forest Region. *In* Degradation of forested lands - forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No 56, pp. 281-286.

This study examined the extent of soil disturbance in the Prince George Forest Region of British Columbia. A variety of slope classes and terrain types, both summer and winter logging, and normal ground-skidding operations were examined. The percent area occupied estimate was obtained from topographic maps (1:5000) and a planimeter. On cutblocks harvested during the summer, 17-19% of the land base was affected by the combined influence of landing, main road, and skid trail construction. On winter-logged cutblocks, the land base affected was between 12 and 18%. On steep terrain (>40%), skid trails accounted for between 16 and 26% of the cutblock area.

Minore, D. 1986. Effects of site preparation on seedling growth: a preliminary comparison of broadcast burning and pile burning. USDA Forest Service, Pac. NW For. Range Exp. Sta. Portland, OR. Res. Note PNW-RN-452. 12 p.

Broadcast-burned and piled-and-burned plantations were studied in southwestern Oregon to determine if burning method affected the growth of Douglas-fir. The measured and potential heights of 5-year-old seedlings were about equal where broadcast burning occurred, but measured heights were less than potential heights on most of the piled-and-burned plantations. Site quality was probably damaged by piling and burning.

Minore, D., C. E. Smith, and R. F. Woodard. 1969. Effects of high soil density on seedling root growth of seven northwestern tree species. USDA For. Serv., Pac. NW For. Range Exp. Sta. Portland, OR. Res. Note PNW-112. 6 p.

Seedlings of Douglas-fir, sitka spruce, western hemlock, western redcedar, lodgepole pine, Pacific silver fir, and red alder were grown over soil columns compacted to bulk densities of 1.32, 1.45, and 1.59 g/cm^3. After 2 years, the roots of lodgepole pine, Douglas-fir, red alder, and Pacific silver fir had penetrated the soil columns at the highest soil density.

Mitchell, M.L., A.E. Hassan, C.B. Davey, and J.D. Gregory. 1982. Loblolly pine growth in compacted greenhouse soils. Trans. ASAE (1982): 304-307, 312.

In a controlled greenhouse study, root growth and seedling performance of loblolly pine grown in pots over a range of soil densities were observed. The soil densities were 1.2, 1.4, 1.6, 1.8 and 2.0 g/cc. Seedlings were grown for 19 weeks and harvested. Root development was found to be inversely related to bulk density, with root mass and surface area (as measured by root absorption capacity) declining significantly after bulk density equalled 1.4 g/cc. The seedling height, shoot mass, and root collar diameter declined with increasing bulk density. The content of N and P per tree also decreased with increasing bulk density. Mycorrhizal development declined with an increase in bulk density (particularly after 1.6 g/cc).

Morris, W.G. 1970. Effects of slash burning in over-mature stands of the Douglas-fir Region. For. Sci. 16: 258-270.

The effects of slashburning after the clearcutting of old-growth coniferous forest in western Washington and Oregon were examined. The soils were loams and the average slopes were 22% in the Cascades and 48% in the Coast. Slashburning resulted in less than 6% of the average burned area being severely burned, and more than 50% was lightly burned.

Olsen, E.D. and J.C. Seifert. 1984. Machine performance and site disturbance in skidding on designated trails. J. For. 82: 366-369.

As part of a study on machine performance, the extent of site disturbance on a 15-year-old site in Idaho was examined. For all machine types, 17% of the conventionally logged whole-tree units and 9% of the units where tree-length logs were skidded on designated trails were calculated to be roaded. A survey of 400 plots (1/300 acre) in this area found 34% of the plots were affected by machines in the conventionally logged units and 21% where trails had been designated. The affected plots had 84-91% of the stems injured or killed. Losses caused by falling timber were noted on 66% of the conventionally logged plots and 79% of the designated plots, with 37% of the trees on the plots dead or damaged irrespective of logging system. Overall loss of regeneration was estimated at 53% for the undesignated units and 48% for the designated units. The difference of 5 percentage points was due primarily to mortality caused by the machines.

Packer, P.E. and B.D. Williams. 1976. Logging and prescribed burning effects on the hydrologic and soil stability behavior of larch/Douglas-fir forests in the northern Rocky Mountains. *In* Proc. Montana Tall Timbers Fire Ecology Conf. and Fire and Land Management Symp., No. 14. Tall Timbers Res. Sta. Tallahassee, FL. pp. 465-479.

The 7-year effects of jammer logging and prescribed burning on forest watersheds with stable soils in western Montana were studied. The area was located in Miller Creek on the Flathead National Forest, having slopes ranging from 20 to 35%, and silty loam soils derived from metamorphosed marine sediments. The bulk density of the soil decreased, and soil porosity and organic matter content of the top 2.54 cm of the soil increased with logging. Burning had the reverse effect following logging. After 7 years there was an improvement in soil bulk density and porosity of the burned soils.

Rollerson, T.P. and C.A. Kennedy. 1984. Compactive effects of a low ground pressure skidder. Woodlands Serv. Div., MacMillan Bloedel Ltd., Nanaimo, B.C. 43 p.

The increasing number of trips with a low ground pressure (LGP) skidder along skid trails caused a trend of increasing bulk density in medium- to coarse-textured (loam to sand) soils on the east side and north end of Vancouver Island. Based on a regression analysis from the Salmon River site, it was determined that 10 turns of the skidder results in an average increase in soil bulk density of approximately 2%, and 100 turns in an increase in density of 10%. Measurements of setting wide soil bulk density before and after logging showed no significant increases in overall densities. Increasing LGP skidder traffic along skid trails resulted in increasing exposure of mineral soil, especially on steeper slopes. Severe rutting can occur with excessive LGP skidder traffic on medium-textured soils under high soil moisture conditions, especially if surface slash and stumps are bladed away.

Ross, D.W. and J.D. Walstad. 1986. Effects of site preparation on ponderosa pine, associated vegetation, and soil properties in south central Oregon. Can. J. For. Res. 16: 612-618.

Six site preparation treatments were evaluated 8 years after installation. Treatments were: logged-only control, ripping, brush blading, disking, herbicide treatment, and herbicide treatment followed by disking. The brush blading and herbicide-disking treatment showed the greatest reduction in soil nutrient levels (total N, S, and C, and extractable P) compared to the control at a depth of 15-25 cm. Brush blading and both disking operations increased soil bulk density in the upper soil zone (0-10 cm).

Schoenberger, M. M. and D. A. Perry. 1982. The effect of soil disturbance on growth and ectomycorrhizae of Douglas-fir and western hemlock seedlings: a greenhouse bioassay. Can. J. For. Res. 12: 343-353.

A bioassay was performed on soil collected in an area of the west-central Cascades in Oregon to determine the effect of soil disturbances on growth and ectomycorrhizae. The soils were collected from an unburned clearcut, a recently burned clearcut, an old-growth forest, a 20-year-old plantation that had been clearcut and burned, and a 40-year-old natural burn. Douglas-fir seedlings had the most total and ectomycorrhizal root tips, and the greatest root weight when grown in soil from the unburned clearcut. There were no differences in top weights of seedlings between soils. Total number of root tips and mycorrhizal root tips were greatest in the soil from the old-growth stand for the western hemlock seedlings. Western hemlock shoots and roots were heavier in the soil from the unburned clearcut.

Schwab, J.W. and W.J. Watt. 1981. Logging and soil disturbance on steep slopes in the Quesnel Highlands, Cariboo Forest Region. B.C. For. Serv. Res. Note No. 88.

The study area is a clearcut site in the Quesnel Highlands, characterized by slopes ranging from 30 to 60% with generally moderately well to well-drained, gravelly sandy loams to gravelly loams. A transect point sampling method was used to determine the amount of area (expressed as a percentage) in each of five disturbance classes within the clearcut unit. The total disturbance on running skyline-yarded clearcuts averaged 34.7% of the cutblock with 3.1% deep (>25 cm depth) disturbance. Crawler tractor-logged clearcuts averaged 62.6% disturbance of the area with 27.8% deep disturbance.

Sidle, R.C. and D.M. Drlica. 1981. Soil compaction from logging with a low-ground-pressure skidder in the Oregon coast ranges. Soil Sci. Soc. Am. J. 45: 1219 -1224.

The effect of a low ground pressure skidder (FMC) on the compaction of a clay loam soil was examined. An increase in the bulk density of the soil on the skid trails was highly correlated to the number of turns with the skidder. The surface 15 cm of the soil was impacted more by uphill than by downhill yarding. Downhill skid trails with 3 or fewer turns, had a less than 10% increase in bulk density. At the 7.5 cm depth, 9 turns increased bulk density approximately 25 and 45% for downhill and uphill yarding, respectively. The levels of compaction were compared to standard engineering compaction tests to see if the laboratory test could be used to estimate potential soil compaction. The modified 10-blow Proctor tests slightly overestimated the increase of bulk density on high-use uphill skid trails. The 15- and 20-blow Proctor tests closely estimated the density increases for the 7.5 and 15 cm depths, respectively, for uphill skidding.

Smith, R.A. 1988a. Environmental impact of ground harvesting systems on steep slopes in the Vernon Forest District. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56, pp.13-27.

Slopes in the Vernon Forest District were examined to assess the environmental impact of conventional ground harvesting systems. A reconnaissance survey of six areas indicated disturbance levels ranging from 17 to 61%. The average cut slope height on skidroads ranged from 0.9 to 2.9 m. Using small crawler tractors to construct skidroads on a snowpack produced the least disturbance and the smallest skidroads. Excessive excavation on many sites often led to slope failure and surface erosion. Regeneration on the compacted surfaces was usually growing poorly or was nonexistent. Many of the skidroads and landings were intercepting surface and/or ground water flow, resulting in surface erosion and channelling of water. Guidelines for skidroad and landings were drafted to minimize site degradation through the modification of harvesting systems, or the use of alternative yarding equipment.

Smith, R.B. and E.F. Wass. 1976. Soil disturbance, vegetative cover and regeneration on clearcuts in the Nelson Forest District, B.C. Can. For. Serv., Pac. For. Res. Cent., Inf. Rep. BC-X-151. 37 p.

This survey was conducted in the West and East Kootenay Regions on slopes of 30-81% (mean of 58%) occurring in three biogeoclimatic zones: Interior Douglas-fir, Interior Western Hemlock, and Engelmann Spruce-Subalpine Fir. The age of logging varied from 0 to 23 years (avg. 5.2). Soil disturbance due to roads (including skidroads) was found to average 39.8% of the area with summer ground skidding, almost twice that for winter ground skidding (21.3%). Very deep disturbance (gouges or deposits over 25 cm deep) produced by roads amounted to 28.3% of the area of summer ground skidding clearcuts, 12.8% of winter ground skidding clearcuts, and 9.1% of summer high-lead and winter high-lead clearcuts. Excluding 0- and 1-year-old clearcuts, mil-acre stocking levels of new regeneration were highest on roads (38.7%) and between roads (33.5%) in the interior western hemlock zone, and lowest on roads (4.1%) and between roads (8.5%) in the interior Douglas-fir/Englemann spruce-subalpine fir transition. Total stocking (new and advance regeneration) was highest on roads (39.8%) and between roads (38.5%) in the IWH zone, and lowest on roads (6.1%) and between roads (11.9%) in the IDF/ESSF transition.

Smith, R.B. and E.F. Wass 1985a. Changes in soil surface conditions at Marl Creek root-rot control site. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Unpubl. Rep. 11 p.

Forest soils from a clearcut harvesting operation at Marl Creek showed alterations in surface soil characteristics due to stumping, windrowing and root raking. The stumped land showed 86% disturbance of its area, while the non-stumped area had 59% disturbance. The stumped area disturbances were caused by stump removal (49%), tractor tracks (34%), skidroads (5%), fireguards (9%), and scalps and skidroad cat trails (3%). In the non- stumped area, disturbances were caused by skidroads (44%), landings (15%), fireguards (5%), yarding (14%), cat trails (17%). erosion (1%), and burning (4%). Bulk densities from the stumping deposit and undisturbed soils were significantly lower than for the inner and outer tracks of the skidroad.

Smith, R.B. and E.F. Wass. 1985b. Some chemical and physical characteristics of skidroads and adjacent undisturbed soils. Can. For. Serv., Pac. For. Res. Cent., Inf. Rep. BC- X-261. 28 p.

Contour skidroads and adjacent undisturbed soils in five steep clearcuts (17-23 years old) in the southern interior of British Columbia were selected for studies of soil characteristics. Trenching, soil sampling and analyses, penetrometer tests, bulk density, and soil temperature measurements were used to explain tree growth and to aid in rehabilitation planning. Soils varied from strongly acid to alkaline and from coarse to medium texture. In undisturbed soils, bulk density and pH increased, while organic C, total N, and fine soil fraction decreased with depth. The inner, gouged portions of skidroads reflected the increase in bulk density with depth with their relatively dense soils and high resistance to penetration. These physical conditions, in addition to relatively low organic matter and N contents, play a large role in reduced growth rates of trees established at this skidroad position. Greater height growth on the outer half of skidroads was related mainly to the less compact soils. Poor growth of trees across the whole skidroad profile on alkaline soils was attributed to a nutritional imbalance aggravated by the absence of surface organic horizons which normally provide a carbonate-free haven for roots. This study also indicated a slow rate of amelioration of disturbed soils, particularly in terms of density, penetrability, carbonate concentration and pH, but marked increases of organic

C and total N as natural revegetation proceeded over a 20-year period. Recommendations for the rehabilitation of these and similar sites are presented.

Steinbrenner, E.C. and S.P. Gessel. 1955b. The effect of tractor logging on physical properties of some forest soils in southwestern Washington. Soil Sci. Soc. Amer. Proc. 19: 372-376.

Selected soil physical properties were measured on 9 tractor-logged areas in southwestern Washington. Results showed that the soils from the tractor-logged cutover had a 35% loss in permeability rate, a 2.4% increase in bulk density, and a 10% decrease in macroscopic pore space. The tractor roads (which occupied 26% of the logged area) showed a 93% loss in permeability, a 15% increase in bulk density, and a 53% loss in macroscopic pore space. Four passes over a skidroad with a HD20-tractor reduced soil macropore space by 50% and infiltration rate by 80%.

Tackle, D. 1962. Infiltration in a western larch-Douglas-fir stand following cutting and slash treatment. USDA For. Serv., Intermount. For. Range Exp. Sta., Ogden, Utah. Res. Note INT-89. 7 pp.

Water infiltration (using 6-inch infiltrometer rings) was determined on a silty-clay loam after timber harvesting near Boseman, Mont. The old-growth western larch and Douglas-fir stand was jammer-logged with D-7 and D-4 tractors constructing the roads. Following the cut and burn, reductions in infiltration were documented. However, infiltration recovered after 5 years except on the excessively compacted surfaces (roads and skid trails).

Taylor, S.W. and M.C. Feller. 1986. Initial effects of slashburning on the nutrient status of Sub-Boreal Spruce Zone ecosystems. Fire Manage. Symp., Prince George, B.C., April 8-9, 1986. 12 p.

Low to moderate slash burns resulted in substantial losses of total N, P, S, K, Ca, and Mg from both mesic bunchberry-moss and subhygric/hygric Devil's club/horsetail-flat ecosystem associations in the Sub-Boreal Spruce (moist) subzone. Nutrient losses as a proportion of total nutrient capital were highest in the mesic ecosystems.

Thompson, S. 1988. Quantification of soil disturbance following logging in the Golden TSA. B.C. Min. For. Lands, Nelson, B.C. Unpubl. Rep.

A study of soil disturbance resulting from timber harvesting in the Golden TSA was completed in the 1986 field season. The primary objectives of the project were to (1) estimate the amount of detrimental soil disturbance resulting from logging, using summer ground-skidding systems; and (2) evaluate the implications of the measured disturbance levels on the Annual Allowable Cut calculation for the TSA. Total detrimental disturbance from skidroads, secondary roads, and landings on slopes greater than 30% averaged 35% (range 23 - 52%), with a resulting productivity loss of 19%. On slopes less than 30%, detrimental soil disturbance averaged 17%, with a productivity loss of 11%. The higher level of disturbance on the steeper slopes (i.e., >30%) resulted from the larger amount of skidroad disturbance (range 15 - 35%) noted on these sites. The wide range of skidroad disturbance levels suggested that significant opportunity exists for minimizing disturbance through better harvest system design, better operator performance, or selection of alternative harvesting systems on difficult terrain. Most sites on slopes >30% had a mean skidroad spacing of less than one tree length. On all slopes, mean landing area on cutblocks greater than 15 ha in size was 3.3%. Proportion of landing area on smaller cutblocks varied with cutblock size.

Watt, W.J. and R.K. Krag. 1988. A comparison of cable and small tractor logging soil disturbance. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56, p. 44-53.

Soil disturbance levels caused by cable and small tractor logging were compared under summer and winter conditions. The area was in the moist subzone of the ESSF phasing into the ICH at lower elevations. The sensitive area, logged by tractor, had Orthic-Humo-ferric podzols on shallow gravelly sandy loams to silt loam morainal and colluvial parent material. The very sensitive area, logged by cable, had Orthic-Humo-ferric podzols on steep, moist, loamy morainal parent materials. Soil disturbance was surveyed on the ground by direct measurement. Areas harvested by the cable system had 10% or less soil disturbance. The areas harvested by crawler tractors had 19.6 and 20.3% disturbance for summer and winter operations, respectively. Winter skidroads had one-half the detrimental soil compaction of summer skidroads.

2 EROSION

2.1 Summary

2.1.1 Surface erosion

Undisturbed forest soils are generally covered with highly porous, permeable accumulations called the forest floor. Thus, high infiltration capacities, which are much greater than normal rainfall intensities, are maintained, and surface runoff does not usually occur. Natural erosion does occur but at almost imperceptible rates. Forest management activities which remove or greatly disturb this organic layer expose the underlying mineral soils to the erosive forces of water, wind and frost and accelerate the rates of erosion. Surface soil erosion is basically a concern for forest road surfaces (primary, secondary, haul- and skidroads) and related cut-and-fill slopes. Several site factors, including soil depth, soil water holding capacity, particle size and shape, precipitation and snowmelt amounts and patterns, soil organic matter content, vegetation and slash cover, soil texture, and clay mineralogy, affect surface soil erosion (Packer 1967).

Carr (1980) describes the progression of unchecked erosion through four stages: 1) splash erosion — the loosening of soil particles by raindrop impact, with resultant destruction of soil structure; 2) sheet erosion — the removal of a fairly uniform layer of mineral soil by surface runoff; 3) rill erosion —the formation of abundant small channels several centimeters in depth; and 4) gully erosion — caused by the rapid accumulation of water in narrow channels, which remove the soil in the channels to a substantial depth. The volume of soil which can be lost through accelerated surface erosion can be enormous with obvious serious impacts. Research has shown that forestry activities can accelerate the rate of surface erosion from 2 to 15 times (Froehlich 1978b; Klock 1982; O'Loughlin 1972; Schwab 1983). Surface erosion as a consequence of forest road building has been observed to remove about 200 m^3 of soil per hectare of exposed slope (Dyrness 1970; Carr and Ballard 1980). The accumulation of this material in the road drainage system greatly reduces the effectiveness of ditches and culverts, thus resulting in road stability concerns. Megahan and Kidd (1972b) found that 85% of the surface erosion recorded over a 6-year period occurred in the first year and 93% had occurred by the end of the second year. These authors also pointed out that stabilization measures such as seeding, planting, mulching, using tackifiers, and installing barriers could reduce the erosion by 99%.

Packer (1967) described how certain road and watershed features could be used in predicting road-related erosion. The amount and severity of road surface erosion is affected chiefly by road grade, proportion of water-stable soil aggregates in the road surface, topographic position, upper slope steepness, and aspect. Sediment movement downslope from logging roads is influenced by cross-drainage spacing, spacing of downslope barriers and their initial distance from cross-drain, road age, downslope barrier type, fill slope cover density, and proportion of soil particles and water-stable aggregates on adjacent undisturbed slopes (Packer 1967).

Other forest management activities (e.g., harvesting, mechanical site preparation, slashburning, and plantation maintenance [vegetation management]), have been demonstrated to alter soil water regimes and decrease soil strength by reducing vegetative cover and root strength. Burning can also increase runoff by creating water-repellent layers on the soil surface (Feller 1982).

Carr (1980, 1985b) and Homoky (1984, 1987) have identified a range of surface erosion and sediment control methods which are adaptable for use in forest management. There are, however, two major constraints to these methods: 1) they will increase the costs of operations; and 2) the establishment of most long-term erosion control systems takes time to become effective and does not help short-term erosion concerns. The methods discussed by Carr (1980, 1985b) can be remedial solutions to clean up and stabilize problem areas or correct mistakes, but they are most effective when incorporated into an overall erosion control plan for a given development area. Cook and King (1983) reported that sediment barriers (cull logs and slash) constructed on fill slopes of new roads were 75-85% effective at trapping sediment.

Prevention of erosion problems through planning and on-site regulation of activities can alleviate much of the concern related to surface erosion, thus minimizing its economic and biophysical impacts (Megahan and King 1985).

2.1.2 Mass movement

Mass movement is defined as the movement of soil and surficial materials by gravity. This can be a slow phenomenon (i.e., soil creep) or it can be a rapid, substantial movement (i.e., landslides). Timber harvesting on steep terrain has the potential to increase the rate of mass movement, particularly on marginally stable slopes. Both roads and clearcutting can contribute alone or in concert to slope failures.

Important factors which govern the magnitude of mass movement include slope gradient, aspect, surficial material, underlying bedrock, hydrologic conditions, and vegetative cover. Many research studies have recorded an increase in the frequency of small, shallow slides with time after logging. These studies have shown also that stability on many of the steep forested slopes may well depend primarily on tensile reinforcement from tree roots, and that this reinforcement decreases as roots decay after logging. These studies are not conclusive, however, because other changes (e.g., in evapotranspiration) are occurring simultaneously, and also because researchers have tended to not normalize their results with respect to differences in precipitation from year to year. Root strength decreases rapidly after clearcutting, resulting in a varying period (likely 2-20 years in the Interior) of acute vulnerability on marginally stable slopes until vegetative regeneration renews the stabilizing root network. Regenerating tree species, speed and nature of regeneration, and time to crown (and root) closure determine the timing and duration of this period of vulnerability. Concern for accelerated degradation because of mass movement should be highest in the wetter interior biogeoclimatic subzones, for example, in the ICH, wetter SBS and ESSF, and BWBS (when soil water/ frost regime is altered).

Dyrness (1967), Megahan *et al*. (1978), and Amaranthus *et al*. (1985) found that roads and road building were associated with 50 - 88% of all landslides inventoried. Roads have been reported to increase mass wasting rates from 25 to 100 times those observed on undisturbed forest slopes in coastal mountains (Amaranthus *et al*. 1985; Rood 1984; Swanston and Swanson 1976). Roads contribute to slope failure by altering the magnitude of pre-disturbance strengths and stresses on the slope through the construction of cuts and fills. The frequency of these failures is closely related to slope moisture conditions, particularly the development of ephemeral water tables during periods of rainfall or snowmelt. Concentration and diversion of drainage by roads because of poorly located or constructed ditches and culverts is often a contributing factor to failures of slopes and fills/sidecasts.

The interpretation of the statistics used here can be difficult (and even misleading) because of changing road-building standards, techniques and equipment used (Megahan 1986).

2.2 Annotated Literature

Amaranthus, M.P., R.M. Price, N.R. Barr, and R.R. Ziemer. 1985. Logging and forest roads related to increased debris slides in southwestern Oregon. J. For. 83(4): 229-233.

Debris slides over a 20-year period were inventoried on 55 000 ha of forested land in the Klamath Mountains of southwest Oregon. Frequency during the study period was about one slide every 4.3 years on each 400 ha —an erosion rate of about 1 m^3/ha per year. Erosion rates on roads and landings were 100 times those on undisturbed areas, while erosion on harvested areas was 7 times that of undisturbed areas. Three-quarters of the slides were found on slopes steeper than 70% and half were on the lower third of slopes.

Roads, occupying only 2% of the area inventoried, were the sites of over half of the slides and 60% of the slide volume. Harvest areas, occupying 10% of the area inventoried, yielded 34% of the slides and produced 18% of the slide volume. The remaining 88% of the study area, which was in a natural condition, produced only 22% of the slide volume.

Both frequency and volume of debris slide erosion in private harvest areas exceeded those in Forest Service harvest areas. Forest Service logging was associated with an almost 6-fold increase in slide volume, whereas private logging was associated with a 45-fold increase. The difference is smaller with respect to slide frequency: a 17-fold increase on Forest Service harvest areas and a 38-fold increase on private harvest areas.

Ballard, T.M. and R.P. Willington. 1975. Slope instability in relation to timber harvesting in the Chilliwack Provincial Forest. For. Chron. 51 (2): 59-62.

This paper discusses specific factors contributing to instability which can be analyzed from interpretations of site conditions in relation to soil shear strength and stress equations. Such analyses can be applied to road planning and timber harvesting to minimize landslide occurrence.

Burroughs, E.D., Jr. and B.R. Thomas. 1977. Declining root strength in Douglas-fir after felling as a factor in slope stability. USDA For. Serv., Intermount. For. Range Exp. Sta., Ogden, UT. Res. Pap. INT-190. 27 p.

The primary objective of the overall project was to identify areas with high potential for slope failure by debris avalanches and/or flows. Five major stability factors were measured: slope gradient, soil depth, pore-water pressure, soil shear strength and root strength. A second objective was to determine the number of trees which could safely be removed from certain sites without causing slope failures through loss of root strength. Both coastal and Rocky Mountain Douglas-fir roots were studied in detail. Coastal Douglas-fir roots were found to be stronger than the Rocky Mountain variety, but they decay faster. The finer roots (1 cm or smaller) decay after 2-3 years and are thought to have the greatest effect on stability.

Chamberlin, T.W. and W.W. Jeffrey. 1968. Soil movement-water quality deterioration associated with timber harvesting in the West Kootenay area. Univ. B.C., Fac. For., Vancouver, B.C. Misc. Publ. 4.

This study set out to fulfill three objectives. First, it examined the major causes of soil movement and water quality deterioration related to logging in the West Kootenay area. Second, it predicted the erosion hazard for different surficial deposits to provide a relative rating useful to land managers. Third, it considered the quantitative soil stability measures which are applicable to the prediction of erosion hazards.

Clayton, J.L. 1981. Soil disturbance caused by clearcutting and helicopter yarding in the Idaho batholith. USDA For. Serv., Intermount. For. Range Exp. Sta., Moscow, ID. Res. Note INT-305. 7 p.

The disturbance to soil from helicopter logging and broadcast burning of slash from a large clearcut was examined prior to and 2 years following logging and burning. The area had 30-50% slopes with coarse-textured, weakly developed soils. Erosion was accelerated on 2% of the area with short-term increase in erosion rates of 10% over the natural rates. Broadcast burning resulted in litter losses on 14% of the treated areas.

Dyrness, C.T. 1967. Mass soil movement in the H.J. Andrews Experimental Forest. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland OR. Res. Paper PNW-42.

The relationship between mass soil movement and the amount of development-caused disturbance was examined in the drainage area of Lookout Creek in the Western Cascades. The mass soil movements occurred during the winter of 1964-1965 as a result of a severe storm. Although over 72% of the mass movements occurred in connection with roads, only 1.8% of the total area of the forest is in road rights-of-way. Only 11% of the events occurred in undisturbed areas.

Fredricksen, R.L. 1970. Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland. OR. Res. Paper PNW-104. 15 p.

The effects of patch logging (using roads) and clear-felling (using skylines) of Douglas-fir forests on soils derived from tuff and breccia were examined. Sedimentation from the patch logging was 100 times greater, and from clear-felling was 3 times greater, than that from an undisturbed area. Landslides were the main source of sedimentation where roads were used, and were most frequent where roads crossed water channels.

Gray, D.H. and W.F. Megahan. 1981. Forest vegetation removal and slope stability in the Idaho batholith. USDA For. Serv., Intermount. For. Range Exp. Sta., Moscow, ID. Res. Pap. INT-271.

A study was conducted on 2 small watersheds in the Boise National Forest to determine the role of forest vegetation in maintaining more secure slopes in shallow, coarse-textured soils typical of the Idaho batholith. Soil water piezometry and soil shear strength measurements were made. Woody vegetation growing on slopes of the batholith were found to contribute to stability by root reinforcement, by soil moisture depletion from interception and transpiration, by regulation of snow accumulation and melt rates, and by soil arching restraint between tree stems. Suggested measures and approaches to deal with slope instability problems were: more stringent controls on size and location of clearcut units; greater use of buffer zones, particularly along haulroads next to streams; and construction of hydraulic structures that divert water away from critical areas.

Helvey, J.D., A.R. Tiedemann, and T.D. Anderson. 1985. Plant nutrient losses by soil erosion and mass movement after wildfire. J. Soil Water Conserv. 40: 168-173.

In the eastern Cascades of Washington, soil erosion and mass movement were examined. The sites had average slopes of 50%, having fine sandy loam soils. Annual sediment loads increased as much as 180 times above pre-fire levels following wildfire in 3 forested watersheds. Losses of sediment-borne nutrients during 5 post-fire years averaged 40 times greater for total N, 14 times greater for available P, 26 times greater for Ca and Mg, 25 times greater for Na, and 32 times greater for K than average values during the 4 years prior to fire. Greatest nutrient losses occurred with debris torrents. Channel scouring was associated with greater runoff, higher peak flows, and debris torrents following fire.

Megahan, W.F. 1974a Erosion over time on severely disturbed granitic soils: a model. USDA For. Serv., Intermount. For. Range Exp. Sta. Ogden, UT. Res. Paper INT-156. 14 p.

A negative exponential equation containing three parameters was derived to describe time trends in surface erosion on severely disturbed soils. The data used to develop the equation parameters were obtained from four different studies of surface erosion on roads constructed from the granitic materials found in the Idaho batholith. The equation allows one to estimate the quantity and timing of surface erosion following disturbance. The model indicates that surface erosion follows an exponential relationship with time, such that by far the largest percentage of soil loss occurs within 1 to 2 years after disturbance.

Megahan, W.F. and W.J. Kidd. 1972b. Effect of logging roads on sediment production rates in the Idaho batholith. USDA For. Serv., Intermount. For. Range Exp. Sta., Moscow, ID. Res. Paper INT-123. 14 p.

The effects of logging road construction on sediment production rates were examined over a 6-year period in an area with granitic bedrock, steep slopes and highly erodible soils. About 30% of the total accelerated sediment production from roads was caused by surface erosion and the remainder by mass erosion. The sediment production rate attributed to erosion within the area disturbed by road construction averaged 770 times greater (220 from surface erosion and 550 from mass erosion) than for a similar undisturbed area. Surface erosion on roads decreased rapidly with time. About 84% of the total sediment for the 6-year period was produced during the first year after constuction. By the end of the second year, 93% of the total sediment was produced. Up to 99% of the sediment which is lost can be retained using the following stabilization treatments: trees, wood chip mulch, straw mulch, jute netting, asphalt-straw mulch, straw mulch-netting and trees, or straw mulch-netting.

Megahan, W.F. and P.N. King. 1985. Identification of critical areas on forest lands for control of non-point sources of pollution. Environ. Manage. 9(1): 7-18.

Most non-point sources of pollution problems can be controlled by careful planning and management of specific critical areas. These include: 1) areas with high hazards for mass erosion and surface erosion; 2) overland flow areas; and 3) riparian zones.

Megahan, W.F., N.F. Day, and T.M. Bliss. 1978. Landslide occurrence in the western and central Northern Rocky Mountain physiographic province in Idaho. *In* Forest soils and land use. C.T. Youngberg (editor). Col. State Univ. Press, Fort Collins, CO. pp. 116-139.

The effect of disturbances on soil was examined in the Northern Rocky Mountains. Road construction accounted for 58% of the landslides in the area. The combination of roads plus logging and/or fire accounted for another 30% of the landslides. In total, roads were associated with 88% of all landslides. Landslides associated with vegetation removal alone accounted for 9% of the slides, burning for 7%, and logging for 2%. Only 3% of the landslides occurred on totally undisturbed areas. With respect to landslides associated with roads, 66% occurred on road cuts (having 47% of the slide volume), 27% on fills with no culverts (having 31% of the slide volume), and 7% on fills with culverts (having 21% of the slide volume). Landslides are most frequent from 4 to 10 years after logging.

Mersereau, R.C. and C.T. Dyrness. 1972. Accelerated mass wasting after logging and slash burning in western Oregon. J. Soil Water Conserv. 27(3): 112-114.

The influence of clearcut logging and slashburning on soil disturbance in a steep watershed in western Oregon was studied. These disturbances resulted in increased rates of soil movement, especially on slopes unprotected by organic debris. During the first growing season after burning, soil movement was most pronounced on 80% slopes (versus 60% slopes), on south aspects (versus north aspects), and in areas having little plant cover (50% versus well-vegetated areas with 75% cover). Soil movement on bare south slopes was 8 times greater than on vegetated north slopes. On the 80% south slopes, there was 26 times more soil movement as on the 60% north slopes. Soil movement on the bare 80% slopes exceeded movement on the vegetated 60% slopes by 46 times. By the second season after burning, the rapid invasion by vegetation essentially halted soil movement on all slopes.

Paeth, R.C., M.E. Harward, E.G. Knox, and C.T. Dyrness. 1971. Factors affecting mass movement of four soils in the western Cascades of Oregon. Proc. Soil Soc. Am. 35: 943- 947.

Four soils in the Western Cascades of Oregon were studied to determine their relationship to slope stability. Soils prone to slope failure were characterized by high amounts of smectite clay, absence of kaolin, and moderate amounts of free iron oxides. The more stable soils contained kaolin, more chlorite and chlorite intergrades, less smectite, and higher amounts of free iron oxides. Colour of the soils and of their source rocks was correlated to landscape stability. Areas with tuff and breccia substratum were the site of 93.6% of mass movements even though only 37.2% of the area consisted of these rocks. Of these mass movements, 63.8% occurred on greenish tuff and breccia, which made up 8% of the forest area; and 29.8% occurred on yellowish and reddish tuff and breccia, which made up 29.2% of the forest area.

Pye, J.M. and P.M. Vitousek. 1985. Soil and nutrient removals by erosion and windrowing at a southeastern U.S. Piedmont site. For. Ecol. Manage. 11: 145-155.

Soil losses from various loblolly pine (*Pinus taeda*) harvest and regeneration practices were investigated at a moderately sloping Piedmont site. Treatments were stem-only vs. whole-tree harvest, chop and burn vs. shear-pile-and-disk site preparation, and the repeated application of herbicide vs. none. Harvest method had no effect on erosion rates over the year measured. Erosion on the chop and burn plots (excluding skid trials) was negligible. Erosion on the disked plots over the same year without and with herbicide was 4 and 10 Mg/ha respectively, representing 5 and 10 kg/ha of total N and 1.3 and 2.5 kg/ha of total P. The measured erosion rates agreed well with Universal Soil Loss Equation estimates. Soil losses due to windrowing were unaffected by harvest method and equalled 254 and 61 kg/ha of prepared area, respectively, after burning. These represent a systematic underestimate of nutrient losses during windrowing. Nonetheless, they are greater than losses in whole-tree harvesting, and they exceed natural inputs expected during a rotation. Losses of this magnitude raise the likelihood of reduced long-term productivity.

Smith, R.B., P.R. Commandeur, and M.W. Ryan. 1984. Vegetation succession, soil development, and forest productivity on landslides, Queen Charlotte Islands, British Columbia, Canada. *In* Proceedings of IUFRO Symp. on Effects of Forest Land Use on Erosion and Slope Stability. C.L. O'Loughlin and A.J. Pearce (editors). Honolulu, HA. pp. 109-116.

Forty-nine landslides (aged 1-155 years) and surrounding terrain were studied in the Queen Charlotte Islands to elucidate vegetation and soil development and impacts on forest productivity. The upper two-thirds of slides had significantly higher bedrock exposure and shallower soils than adjacent terrain. This, coupled with the initial destruction of vegetation, resulted in a greater extent of exposed soils and a lower cover of vegetation than in adjacent logged areas for at least 60 years. Because of lower growth rates caused by relatively poor soil conditions and competition by red alder, production of wood on slides to 60 years was estimated at 30% of that produced in similarly aged logged stands.

Swanson, F.J. and C.T. Dyrness. 1975. Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology 3: 393-396.

The history of landslides in the H. J. Andrew Experimental Forest was followed using data obtained from previous studies, aerial photos taken over 26 years, storm records, and field observations. Slide erosion in clearcut areas in the lower zone was 2.8 times greater than in forested areas, and after road cutting was 30 times greater than on forested sites. The combined effects of roads and clearcutting over a 20-year period, produced a 5-fold increase in landslide erosion compared with undisturbed areas. In the stable zone, only 2 small landslides recorded were related to road construction. However, in the unstable zone, 139 landslides were associated with road construction during the same period.

Swanston, D.N. and F.J. Swanson. 1976. Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest. *In* Geomorphology and engineering. D.R. Coates (editor). Dowden, Hutchinson, & Ross, Inc. Stroudsburg, PA. pp. 199-221.

Factors controlling mass erosion processes, including creep, slump, earthflow, debris avalanching and debris torrents, are presented. The characteristics of movement, rate and occurrence of each of the process types are discussed in detail with particular reference to the Pacific Northwest. The impact of forest operations on mass erosion is also discussed for each process type. Debris torrents are influenced by increased debris avalanche activity, increased concentrations of unstable debris in channels during harvesting, and possible increased peak discharges subsequent to logging. All mass erosion processes can be linked and they can combine to form a major means of natural transport of soil material to streams in the Pacific Northwest.

Wu, T.H. and D.N. Swanston. 1980. Risk of landslides in shallow soils and its relation to clearcutting in southeastern Alaska. For. Sci. 26 (3): 495-510.

A significant increase in the frequency of landslides in shallow soils on hillside slopes of southeastern Alaska following clearcutting has been observed. This phenomenon relates to the loss of root strength and evapotranspiration stress that follows the cutting of trees. A method for evaluating the landslide risk is described in this paper.

3 PRODUCTIVITY LOSSES

3.1 Summary

Soil disturbance caused by harvesting and forest renewal activities often increases the chances of forest regeneration and may increase tree productivity, at least in the short term. Research and operational trials have reported, however, that forest productivity is most often decreased when excessive soil disturbance occurs. Observed changes in tree productivity after various forest management activities are generally the manifestation of a synergism of alterations in many forest site variables (Ballard 1988; McNabb and Campbell 1985).

While the estimating of real or possible productivity decreases resulting from soil degradation is a complex issue, many authors have attributed growth losses in several commercial tree species to soil degradation effects (Carr 1985a; Cochran and Brock 1985; Froehlich 1976, 1979a, b, c; Froehlich and Berglund 1979; Froehlich *et al*. 1986; Hatchell *et al*. 1970; Helms and Hipkin 1986; Jakobsen 1983; Lockaby and Vidrine 1984; Moehring and Rawls 1970; Perry 1964; Smith and Wass 1979, 1980; Thompson 1988; Wert and Thomas 1981; Youngberg 1959). On the other hand, some researchers have found increased stocking levels and/or growth on or near skidroads (Pfister 1969; Smith and Wass 1976, 1979, 1980). Such phenomena, which have been casually observed on many sites in B.C., are, however, not well documented and are not the norm.

There are few studies from B.C. which report the adverse effects of harvesting and forest renewal activities on soils and site productivity; and very few from B.C. or anywhere else which have documented no or positive impacts of deep soil disturbance on site productivity. To derive standards and expectations for our forested land base, we have two options: we can rely on information derived in other parts of the Pacific Northwest or other continents, and we can interpret and apply these to B.C.; or we can rely on research data generated in B.C. Unfortunately, we do not have a comprehensive, well-funded research program with the explicit objective of determining the extent of soil degradation caused by forest harvesting and renewal and the impacts of these activities on site productivity. Until we have such a program, comprised especially of long-term studies, we have to rely primarily on existing literature data and our in-province soils and forestry expertise.

3.1.1 Harvesting effects on productivity

The major degradation effects of conventional, ground-based harvesting activities are soil compaction, soil displacement, scalping, and interruption of site hydrology. All these degradation effects have been shown to be associated with poorer survival and initial growth of planted seedlings, decreased stocking levels and growth of natural regeneration, and longer-term decreases in conifer growth.

Soil compaction effects on tree growth depend on the level of compaction, soil texture, and tree species (Cannell 1977; Halverson and Zisa 1982; Helms and Hipkin 1986). Greacen and Sands (1980) compiled an extensive review of the effects of soil compaction on tree growth and found that in 142 studies reported, 117 (24 species) showed significant yield reductions, 12 (1 species) showed yield increases, 8 (0 species) observed both yield reduction and increase, and 5 (1 species) found no effect on yield. They concluded that, based on H. A. Froehlich's work in the Pacific Northwest and from data on growth reduction associated with increased bulk density, about a 15% reduction in volume yield due to compaction from tractor logging can be predicted. Bulk densities have been reported to restrict tree growth at the following values: >1400 kg/m^3 for loblolly pine (Gent *et al*. 1983; Mitchell *et al*. 1982), 1500 kg/m^3 for radiata pine (Minko 1975), >1330 kg/m^3 for Douglas-fir (Heilman 1981), and >1200 kg/m^3 for pitch pine, Austrian pine and Norway spruce (Halverson and Zisa 1982). From these and other data, it appears that a soil density value in the range of 1200-1400 kg/m^3 is a critical threshold above which tree root growth will be reduced for the range of soil types and tree species in B.C.

Wert and Thomas (1981) reported that, after 32 years in a tractor-logged clearcut, the skidroads (10% of the total area) had produced 74% less volume and had 41% fewer trees than the undisturbed areas, the transition zones (18% of the total area) had 25% less volume and 17% fewer trees than the undisturbed areas, and heavy soil compaction still persisted over 25% of the clearcut. Their major conclusion was that untreated skidroads from tractor logging reduced total tree volume for the rotation in the entire harvest area by at least 11.8%. For the purposes of interpretation and application in B.C., it appears reasonable to project compaction-induced volume reductions over the entire harvest area in the range of 10-15% (Carr 1987a; Froehlich 1979a, 1988; Smith and Wass 1979; Utzig and Walmsley 1988; Wert and Thomas 1981).

Little information exists with respect to the effects of soil displacement on site productivity. Through scalping or gouging and removal/burial of nutrient-rich soil layers, the surface growing environment can be altered substantially, thus providing harsher conditions for regenerating conifers. Major areas of concern are locations of extensive scalping with calcareous, shallow, coarse-textured or strongly podzolized soils (Smith and Wass 1979, 1980, 1985b). Regeneration delays, reduced stocking levels, decreased growth rates and, in some cases, no regeneration at all, can be some of the effects of soil displacement (Carr 1985a).

Megahan (1972) reported that seepage interception by forest roads on sloping ground can deplete soil moisture supplies to below-road sites. Such interception of water and nutrients can reduce productivity of sites below roads. Others, however, have shown an increase in tree growth in a band of trees adjacent to the lower edge of logging roads (Pfister 1969). In this case, the roads examined were outsloped roads and water availability was improved in these areas. Insloped roads can decrease water availability downslope but increase water availability upslope. The available data are so rare and inconclusive that no conclusions can be drawn from the reported research. However, proper site analysis and planning, and informed supervision of road construction and maintenance, can minimize subsurface water flow disruption.

Surface erosion, if allowed to develop to severe levels, can eliminate all vegetative growth for extended periods of time, resulting in a 100% conifer productivity loss for the rotation. While harvesting does accelerate surface erosion, it is difficult to quantify the on-site effects unless there has been serious exposure and removal of the upper mineral soil horizons. If such conditions have resulted, even the deployment of erosion control and surface stabilization measures may not allow the production of a commercial forest crop over the length of the rotation. The obvious solution here is the same as that given above for minimizing the disruption of subsurface flows: appropriate site evaluation and planning, informed on-site supervision of activities, prompt response to developing problems, and post-harvest monitoring of sites.

There are a few literature reports of improved stocking and/or tree growth in areas of disturbed soils (Pfister 1969; Smith and Wass 1976, 1979) and several undocumented field observations of similar conditions. The reports suggested reasons to explain the improved productivity, (e.g., site-specific improvements in moisture availability, increases in soil temperatures, reductions in vegetative competition, and increases in soil strength), but there is not enough information to produce general conclusions and specific guidelines as to specific site conditions which might be improved through disturbance caused by harvesting.

3.1.2 Site preparation effects on productivity

The goal of proper site preparation is to improve regeneration success by providing seedlings with better soil temperature and moisture conditions, decreased competition from other vegetation, and increased light availability. This goal can be achieved through several means: mechanical site preparation, prescribed burning or chemical site preparation. Almost all the research information available relates to the short-term effects of site preparation on seedling survival and early growth. We have very little information available on impacts of site preparation on soil properties and long-term site productivity.

Despite this dearth of information, one major trend is clear: the site preparation treatments most likely to cause adverse impacts on soils and reductions in tree growth are windrowing, scalping and blade scarification (Ballard 1977; Ballard 1985; Herring and McMinn 1980; Smith and Wass 1983b).

These produce height, diameter and volume responses of +18% to -80%, +8% to -61%, and +19 to -40%, respectively. While the positive numbers reflect positive responses to disturbance, these appear to be the rare exceptions rather than the rule.

Given the small information base, the logical general conclusion is that the use of such drastic mechanical treatments should be minimized and that other types of treatments should be tested. Utzig and Walmsley (1988) concluded that whole treatment area reductions in productivity caused by windrowing, bunching, and blade scarification amount to 20, 15 and 10%, respectively. Other MSP equipment is being tested in B.C. through FRDA-sponsored research. These research sites have only recently been installed, but they will be available for long-term monitoring of tree growth and changes in soil properties.

Short-term prescribed fire effects on the major factors affecting tree nutrition and growth are reasonably well understood, but Feller (1982) noted that for each positive or negative effect reported it is possible generally to find the opposite effect reported elsewhere. For example, tree growth on burned sites may be poorer (Knight 1964), perhaps better (Vihnanek 1985), or appear no different from that on unburned sites (Curran 1986).

In both the short and the long term, it may be difficult to resolve relationships between tree performance and fire effects on individual growth factors (Curran 1986). The natural system is complex and dynamic; while some growth factors may be negatively affected, the overall effect of prescribed fire on growth may be favourable because of a positive change in the "most limiting factor." For example, the actual relationship between fire and nutritional status may be altogether different than for growth. Ballard (1985), on research sites near Prince George, found better growth but poorer nitrogen status in planted white spruce on burned sites. He attributed the growth enhancement to the improvement of severe, growth-limiting soil temperatures (Dobbs and McMinn 1977). Also, even if the total nutrient capital of a site is reduced, nutrient availability may increase or may not reach growth-limiting levels (Mroz *et al.* 1980).

While prescribed fire may result in increased or decreased short- term tree growth (Feller 1982), the long-term effects of burning on tree nutrition and growth have not been well studied. It is not known whether the accomplishment of the short-term goals of prescribed burning (i.e., improved and prompt plantation establishment) is at some long-term tree growth cost. However, if some soil degradation results through slashburning, there may be means of mitigating this degradation later in stand life (e.g., through fertilization).

3.2 Annotated Literature

Carr, W.W. 1985a. Restoring productivity on severely degraded forest soils in British Columbia. Ph.D. thesis, Univ. B.C., Fac. For., Vancouver, B.C. 132 p. and appendices.

This study examined forest productivity on landings in the Fort St.James area of B.C. Both summer and winter landings had bulk densities exceeding 1400 kg/m^3, with soil compaction evident at 20- to 30-cm depths. Soil N and available P were also found to be substantially lower following scarification during construction. The tree height growth (lodgepole pine) was 46% lower on summer landings and 30% lower on winter ones. On the stands logged 11 years previously, both summer and winter landing areas exhibited a 60% reduction in height.

Cochran, P.H. and T. Brock. 1985. Soil compaction and initial height growth of planted ponderosa pine. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland, OR. Res. Note PNW- 434. 4 p.

In central Oregon the influence of soil compaction from logging was examined in terms of its effect on tree growth. The site had gentle slopes with deep, well-drained fine loams (50-60 cm) over colluvium. Average total height and average periodic annual height increment of ponderosa pine seedlings planted in clearcuts were negatively correlated with increasing soil bulk density.

Curran, M. 1986. Short and long-term effects of slashburning on soil properties, tree growth and nutrition on some coastal B.C. sites. Univ. B.C., Dep. Soil Sci., Vancouver, B.C. Unpubl. paper presented at NW Fire Council Annual Meeting. 37 p.

The results summarized in this paper are preliminary and incomplete but have shown generally that tree growth and nutrition results varied with species and time since treatment. The following tentative conclusions were presented:

1. Fire sometimes results in reductions in foliar nutrient concentrations in tree foliage;
2. Long-term tree growth is sometimes stimulated by prescribed fire (regardless of effects on nutritional status), sometimes less vigorous after burning, and sometimes unaffected;
3. A number of fire impact variables (total fuel consumption, large fuel consumption, and duff reduction) appear to provide a good index of long-term fire impact on forest productivity;
4. Severe burns which kill root systems can lead to reduced competition. Less severe burns can result in increased competition from vegetation and the related effects on tree growth may persist for some time; and
5. Low-impact fires may promote mycorrhizal colonization of western redcedar roots, but high-impact fires seem to result in less colonization.

Froehlich, H.A. 1973. The impact of even-age forest management on physical properties of soils. *In* Even-age management. R.K. Hermann and D.P. Lavender (editors). Oreg. State Univ., School For., Corvallis, OR. pp. 199-220.

This paper summarizes some of the productivity studies done concerning compaction. It was found that the effects of compaction on seedling growth vary greatly between soils and with tree species. There is a consistent trend toward a reduction of both seedling root length and shoot or leader growth. Losses in height growth range from 14 to 53%. The trend for growth by residual trees affected by compaction is also correlated negatively with density and may range from a relatively small reduction to over 40% loss in growth on individual trees.

Froehlich, H.A. 1979a. Soil compaction from logging equipment: effects on growth of young ponderosa pine. J. Soil Water Conserv. 34: 276-278.

The effect of compaction on the growth of residual ponderosa pine was examined. Soil bulk densities in skid trails at 7.6 and 15.9 cm, and 22.9 and 30.5 cm depths were 18 and 9% greater than those of adjacent undisturbed soils 16 years after logging. Growth was negatively related to the intensity of soil compaction in the root zone. Moderately impacted trees showed a 6% reduction in growth rate and heavily impacted trees showed a 12% reduction over 16 years.

Froehlich, H.A. 1979b. The effect of soil compaction by logging on forest productivity. Report to BLM, Contact No. 53500-CT4-5(N). Oreg. State Univ., For. Engineer. Dep., Corvallis, OR. 45 p.

Growth rates of 22-year-old western hemlock near Seaside, Oregon, were found to be affected by skid trails produced by commercial thinning with small tractors. Growth response averaged 15% less for trees with moderate soil impact in their root zone.

Froehlich, H.A. and E.R. Berglund. 1979. The effect of soil compaction during thinning on the growth of residual trees. *In* Rep. to BLM, Contract No. 53500-CT4-5(N). Oreg. State Univ., For. Engineer. Dep., Corvallis, OR. 19 p.

This study examined the effects of track and wheeled skidders on soil density and the growth of residual trees in a Douglas-fir stand in Oregon which had been thinned 5-15 years beforehand. Compaction of the loamy soils had occurred due to the use of thinning equipment, resulting in 60% of the trees on the heavily compacted sites (>10% increase in bulk density, >40% of the area compacted) having lower growth rates after thinning (30% reduction). Fourteen percent of the trees in the moderate compaction class (major impact is more than 2 m from the stem) had lower growth rates (14% reduction) after thinning. Four percent of the lightly disturbed trees had reduced growth rates.

Froehlich, H.A., D.W.R. Miles and R.W. Robbins. 1986. Growth of *Pinus ponderosa* and *Pinus contorta* on compacted soil in central Washington. For. Ecol. Manage. 15: 285-294.

Growth in height, diameter, and volume was measured on 9- to 18-year-old ponderosa pine and 10- to 13-year-old lodgepole pine trees growing on or near compacted skid trails in the Yakima Indian Reservation in south-central Washington. Soil bulk density of the 0- to 30.5-cm deep layer was measured with a single-probe nuclear densiometer on two sides of each sample tree, and in adjacent undisturbed soil. On three ponderosa pine sites logged 23 years earlier, the average bulk density on skid trails was 15% higher than on adjacent undisturbed soil, and was 28% greater on a lodgepole pine site logged 14 years earlier. At the level of the mean increase in soil bulk density, total height, diameter, and volume growth of ponderosa pine were reduced by 5, 8, and 20% respectively. The growth of lodgepole pine was not significantly related to the increase in bulk density of the soil.

Graham, R.T., A.E. Harvey, J.R. Tann, and M.F. Jurgensen. 1987. Soil organic reserves and their importance to conifer performance in the northern Rocky Mountains. USDA For. Serv., Intermount. For. Range Exp. Sta., Moscow, ID. Unpubl. Rep. 2 p.

Disturbances which removed the surface organic soil layers by scalping adversely affected both bulk density and organic matter content of the soil. The bulk density increased from 0.66 g/cm^3 to 0.93 g/cm^3, and organic matter content decreased from 25 to 11%. The removal of the organic layer decreased the productivity of western white pine by 0.77 m^3/ha per yr, and Douglas-fir by 1.6 m^3/ha per yr.

Halverson, H.G. and R.P. Zisa. 1982. Measuring the response of conifer seedlings to soil compaction stress. USDA, For. Serv., NE For. Exp. Sta. Res. Pap. NE-509. 6 p.

A test of seedling growth response to several levels of soil compaction showed that root penetration depth was best correlated with soil compaction. Shoot biomass, root biomass, root elongation, and seedling height were not well correlated with compaction. The results revealed that most measurements of growth do not give a good indication of seedling response to stresses induced by compaction. There were good partial correlations between mean seedling height and all other measures of growth, but relationships must be developed for each growth response.

Helms, J.A. and C. Hipkin. 1986. Effects of soil compaction on tree volume in a California ponderosa pine plantation. W. J. Appl. For. 1 (4): 121-124.

Soil bulk density was measured around 423 trees (0.48 ha) in a 16-year-old ponderosa pine plantation in the Sierra Nevadas. Landings, skid trails, and areas adjacent to skid trails had soil bulk density increases of 43, 30 and 18%, respectively, compared to areas with lowest bulk density. Due to differences in mean tree volume and initial survival, volume per unit area in these 3 locations was reduced by 69, 55 and 13%, respectively. Areas between skid trails were relatively unaffected.

At full stocking, reduction in productivity by age 40 years in the most heavily compacted areas was thought to be the equivalent of about one site class. Further reduction in projected volume on highly compacted areas could occur due to lower initial survival. Alternative approaches to skid trail management are suggested: 1) minimize the proportion of land used for skid trails and landings; 2) encourage the specification of direction of tree-felling, keep tractors on the designated skid trails, and yard logs by end-lining; 3) designate skid trails as permanent access systems for thinning and harvesting and leave them unplanted; and 4) if no thinnings are anticipated, plant the skid trails and leave them to grow at a reduced productivity level, or till and plant.

Herring, L. J. and R.G. McMinn, 1980. Natural and advance regeneration of Engelmann spruce and subalpine fir compared 21 years after site treatment. For. Chron. 56: 55-57.

The mean height growth of advanced Engelmann spruce 21 years after release by overstory harvesting and residual tree felling was 8 times that of natural regeneration established following brush blade scarification.

Subalpine fir advanced growth was 9 times taller than natural regeneration established on scarified soil. Mean current annual height increment of Engelmann spruce and subalpine fir advanced growth was 39 and 34 cm, respectively, compared with only 7 cm for natural regeneration on scarified soil. The poor performance of natural regeneration on mineral soil exposed by blade scarification is attributed to removal of organic and top mineral soil horizons beyond the immediate reach of seedlings.

Kraemer, J.F. and R.K. Hermann. 1979. Broadcast burning: 25-year effects on forest soils in the western flanks of the Cascade Mountains. For. Sci. 25 (3): 427-439.

Analysis of burned and unburned plots established between 1947 and 1953 in Oregon showed no significant differences after 25 years. Properties were similar for organic matter levels (14.7% unburned, 14.4% burned), total N (0.31%, 0.33%), Ca (13.1 meq/100g, 15.6), K (501 ppm, 525 ppm), P (291 ppm, 360 ppm), and permeability (0.745 kg/cm^2, 0.660). Other soil groups were examined and similar results obtained.

Laing, L.E. and S.W. Howes. 1988. Detrimental soil compaction resulting from a feller buncher and rubber-tired skidder timber harvest operation: a case study. *In* Degradation of forested land: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 191-195.

A monitoring project was conducted in 1983 on a timber sale unit on the Colville National Forest (1) to quantify the degree and extent of detrimental soil disturbance following clearcut, whole-tree harvest with a feller buncher and conventional rubber-tired skidder; and (2) to determine if soil management direction had been met in the Pacific Northwest Region of the USDA Forest Serice. Soil disturbance assumed to be detrimental to plant growth was measured on 42% of the 13.8-ha unit. Most of this disturbance (98%) was detrimental compaction indicated by a bulk density increase of 20% or more over the before-activity level at a soil depth of 10-15 cm. The mean bulk density increase of the detrimentally compacted sample points was 36%. Pacific Northwest Region specifications, that a minimum of 80% of an activity area be left in a condition of acceptable productivity potential for trees and other managed vegetation following land management activities, had not been satisfied in this instance. A loss of 15% of the total potential yield was projected during the next rotation because of detrimental soil compaction, unless effective remedial measures were implemented immediately.

McLeod, A.J. 1988b. A procedure for quantifying the volume loss associated with degraded areas and transition zones in the Prince George Forest Region. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 287-289.

This paper estimates the volume loss associated with the degraded area and transition zone on cutblocks in the Prince George Region. This procedure is based on the volume losses found by Wert and Thomas (1981) on skid trail transition zones (transition zones are considered to encompass an area 3 m in width and lying adjacent to the degraded land) and can be used to estimate skidroad, transition zone, and total cutblock volume losses. Using the estimates of productivity losses on unbladed trails and the proportion of transition zone to skid trail disturbance found by Wert and Thomas, this paper concludes that volume reductions on bladed skid trails in the Prince George Forest Region are 100%, and that transition zone losses amount to a 24.6% reduction in volume.

Miles, D.W.R., F.J. Swanson, and C.T. Youngberg. 1984. Effects of landslide erosion on subsequent Douglas-fir growth and stocking levels in the western Cascades, Oregon. Soil Sci. Soc. Am. J. 48: 667-671.

The effect of landslides on timber growth potential of forest land was estimated by examining a 30-year history of clearcutting and landsliding in the western Oregon Cascades. Height growth and stocking on naturally regenerated landslides were compared on nearby, artifically regenerated clearcut areas of similar aspect, elevation, ages and slope position. Average height growth of 5- to 18-year-old Douglas-fir on the landslide areas was reduced by 62%, and average stocking level was reduced 25% from the clearcut level.

Minore, D. 1986. Effects of site preparation on seedling growth: a preliminary comparison of broadcast burning and pile burning. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland, OR. Res. Note PNW-RN -452. 12 p.

In an area of southwest Oregon, the effects of site preparation treatments (broadcast burning versus pile and burn) were compared. The measured heights of the Douglas-fir trees growing on the piled and burned sites were lower, averaging 83.7 cm, compared to the tree heights from the broadcast-burned sites, averaging 100.8 cm.

Schwab, J.W. 1988. Mass wasting impacts to forest land: forest management implications, Queen Charlotte Timber Supply Area. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B. C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 104-115.

A survey was carried out of mass wasting in the Rennell Sound area on the Queen Charlotte Islands in terms of its impacts on long-term productivity. A theoretical timber productivity loss based on inferences from the study suggest that a non-recoverable land loss from mass wasting, if reflected over the short-term harvest, could result in a 15165 m^3/yr reduction in the allowable cut from the Queen Charlotte Timber Supply Area.

Smith, R.B. and E.F. Wass. 1979. Tree growth on and adjacent to contour skidroads in the subalpine zone, southeastern British Columbia. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Report BC- R-2. 26 p.

Natural regeneration of Engelmann spruce and subalpine fir established on, above, and below contour skidroads on steep clearcuts (9-22 years old), was examined in southeastern B.C. Tree growth was adversely affected on skidroads constructed on medium to fine-textured soils derived from alkaline parent materials. On these soils, reductions in site productivity based on height growth, prorated over the entire clearcut, were estimated as high as 15% for subalpine fir and 12% for Engelmann spruce. However, disturbance on moderately coarse textured, acid soils on cool aspects was judged to be beneficial to tree growth.

Smith, R.B. and E.F. Wass. 1980. Tree growth on skidroads on steep slopes logged after wildfires in central and southeastern British Columbia. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-R-6. 28 p.

The growth of Douglas-fir, western larch, lodgepole pine and Engelmann spruce on contour skidroads was measured 16-18 years after salvage logging of steep wildfire-burnt areas. The study areas were located in the IDF, IDF/ESSF, ICH, ICH/ ESSF, and ESSF zones. When comparing trees on the skidroads and adjacent (above and below) non-roaded surfaces, growth varied with species, soil and climate. A system was thus devised to rate sites on their sensitivity to disturbance according to tree growth on the disturbed surfaces. Tree growth was reduced most on calcareous or strongly acid, coarse-textured or shallow soils in wet climates. The least sensitive sites were those with slightly acid, non-calcareous, medium to moderately coarse- textured soils in dry climates.

Thompson, S. 1988. Quantification of soil disturbance following logging in the Golden TSA. B.C. Min. For. Lands, Nelson, B. C. Unpubl. Rep.

In a study of soil disturbance resulting from conventional timber harvesting in the Golden TSA, total detrimental soil disturbance from skidroads, secondary roads and landings on slopes >30% averaged 35% (range 23 - 52%), with a resulting productivity loss of 19%. On slopes <30%, detrimental soil disturbance averaged 17%, with a productivity loss of 11%. The higher level of disturbance on the steeper slopes (i.e., >30%) resulted from the larger amount of skidroad disturbance (15 - 35%) noted on these sites. This wide range of skidroad disturbance levels suggested that significant opportunity exists for minimizing disturbance through better harvest system design, better operator performance, or selection of alternative harvesting systems on difficult terrain.

Utzig, G.F. and M.E. Walmsley. 1988. Evaluation of soil degradation as a factor affecting forest productivity in British Columbia: a problem analysis. Can. For. Serv., Pac. For. Cent., Victoria, B.C. FRDA Rep. 025. 111 p. and appendices.

This problem analysis examines the potential impacts of various categories of soil degradation on forest productivity. These potential reductions in forest growth are then applied to areal estimates of soil degradation and normal growth rates to estimate potential volume losses, and their impact on the annual allowable cut and the provincial economy. All productivity studies reviewed by the authors had looked at changes in productivity caused by the alteration of a variety of site factors other than just the soil. Consequently, the determination of actual or potential productivity losses due to soil degradation is a complex and difficult problem. Through their analysis of the literature and B. C. data, the authors believe that productivity losses for conventional ground-skidding operations are 12.5% over the harvested area as a whole; for windrowing, bunching, and blade scarification treatments, 20, 15 and 10%, respectively, on whole treatment areas; for prescribed burning, 5% overall; and for eroded areas, 100%.

Wert, S. and B.R. Thomas. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Sci. Soc. Am. J. 45: 629-632.

This Oregon study examines the effects of tractor logging on the productivity of a subsequent stand of Douglas-fir at an age of 32 years. Disturbances occurred from skidroads (10% of the area) and transition zones (3 m on each side of the skidroads, occupying 18% of the area). Soil bulk density (measured by a two-probe nuclear densiometer) in 25% of the study area was found to be heavily compacted (>1.20 g/cm^3) after 32 years. Recovery from compaction had occurred in the surface 15 cm. Total tree volume per hectare for skidroads, transition zones, and undisturbed areas were 34.1, 97.2 and 128.9 m^3; stand densities were 693, 974, and 1180 stems per hectare, respectively. Growth reductions on the skid roads and in the transition zones resulted in an overall volume loss of 11.8% for the entire area.

Youngberg, C.T. 1959. The influence of soil conditions following tractor logging on the growth of planted Douglas-fir seedlings. Soil Sci. Soc. Am. Proc. 23: 76-78.

The growth of planted Douglas-fir seedlings on reddish brown Latosol soils in two cutovers in the Cascade Mountains of Western Oregon was measured. Seedlings were planted in the cutover, berm, and roads. Survival was over 90% for seedlings for all conditions. After 2 years, growth was significantly different between all conditions (1.2 m on the road, 1.6 m on the berm, and 2.1 m on the cutover).

4 REHABILITATION

4.1 Summary

As more and more has been learned about soils and soil degradation, it has become increasingly apparent that effective planning and high operational standards can minimize or eliminate much of the soil degradation associated with forest road development, harvesting operations, and site preparation. However, for the unanticipated or the unavoidable soil degradation, the land manager must have various soil rehabilitation techniques available for immediate implementation. Land managers face two general categories of soil degradation with which they can deal: restoration of site productivity, and erosion control (i.e., prevention of further damage).

4.1.1. Erosion control

Reduction of on-site problems (e.g., reduction of road maintenance costs, enhancement of soil stability, and prevention of site productivity losses) has usually been secondary to off-site considerations in B.C. In 1978, the Research Branch of the Ministry of Forests began the first major erosion control program in the B.C. forestry community. The main aspect of this program was using live plants as building materials for erosion control and landscape restoration.

This program has developed in three stages. The first involved establishing grass-legume cover crops to control surface erosion (Carr 1980; Homoky 1984). The projects initiated (EP's 818 and 834) were concerned with the development and testing of seeding methodology and equipment in forestry. Hydroseeding proved to be highly effective for grass-legume establishment on infertile steep slopes generally found along forest roads. These projects have also played an important role in the development of helicopter hydroseeding for use on landslides in steep, inaccessible areas. The second phase investigated propagation methodology for native shrubs and field-tested the effectiveness of various species for land rehabilitation (Homoky 1984; Marchant and Sherlock 1984). Several field trials were established between 1981 and 1984. The third part of the program involved the development and testing of new erosion control mats. Several types of mats are currently being assessed for erosion control capability, enhancement of vegetation establishment, and cost- effectiveness.

Landslide rehabilitation methodology has been developed in trials initiated on the Queen Charlotte Islands (EP 834). The first challenge of these trials was to control surface erosion and sediment production from landslide areas. Helicopter hydroseeding techniques were developed and successfully tested during these trials. The second phase of the rehabilitation dealt with the establishment of native shrubs to further enhance slope stability. The third step was reforestation with commercial tree species. Studies have shown that conifers which do establish on landslides usually do not grow very well, particularly on the upper 1/5 to 2/3 of most slides, and cannot be considered part of the productive crop for the current rotation. On the lower depositional portions of landslides, where alder competition is controlled (but not eliminated), conifers should be expected to grow quite well.

4.1.2 Restoration of site productivity

Research evidence seems to indicate that the present rehabilitation techniques are incapable of restoring full site productivity (Andrus and Froehlich 1983; Carr 1986d), although tillage and other practices can restore a significant proportion of the growth losses (Froehlich and McNabb 1984). Such treatments appear to rely on creating particular soil properties and restoring organic matter levels so that reconsolidation does not result. Soil rehabilitation activities aimed at restoring forest productivity on excessively disturbed soils began in B.C. in the mid-1970's.

The first landing and skidroad reclamation guidelines in B.C. resulted from landing rehabilitation trials in the Cariboo Forest Region. These guidelines specified decompaction of the soil to a depth of 30 cm, grass seeding for erosion control, and reforestation. They have served as a basis for guidelines adopted in the other interior forest regions. Some recent studies have attempted to verify the effectiveness of the rehabilitation guidelines and to provide a basis for improved operating procedures. There are some general conclusions from these studies:

1. The bulk density increases observed in winter-logged areas, while still less than those found in areas of summer logging, can be great enough to affect future tree growth adversely and may warrant attention equal to that given to rehabilitating summer-logged areas (Carr 1985a);
2. The replacement of the scalped organic matter and the regeneration of soil nutrient availability should be a a prime objective of the rehabilitation project (Carr 1985a); and
3. Soil decompaction alone will not usually sustain commercial tree growth (Carr 1985a).

Another recent study examined the standard landing rehabilitation practices used in the Prince George Region (Carr 1986a) and showed that standard decompaction methodology (rock ripper) did not restore soil conditions to the point of sustaining tree growth. The ripper produced only 26% shatter of the compacted profile, and the portion of the profile that was decompacted had recompacted within a year to a density >1400 kg/m^3. Because of a lack of soil organic matter, stable aggregates did not form after tillage. Total soil nitrogen and available phosphorus were below deficiency levels for commercial lodgepole pine growth. Recent trials with a winged subsoiler in the Prince George Region proved to be very successful in decompacting landings. Soil profile shatter exceeded 80% and the depth of the ripping averaged 40-50 cm (Carr 1986d). However, recompaction still appears to be a problem after this treatment. Recently initiated research in the Prince George Region has focused on the enhancement of soil organic matter content and nutrient levels. The feasibility and effectiveness of topsoil replacement is being tested in conjunction with the use of legumes as a "green manure" crop.

Utzig and Walmsley (1988) recommended that, if rehabilitation is deemed to be cost-effective, there should be more emphasis paid to rehabilitating those sites directly degraded by forest harvesting practices (i.e., landings and skidroads) because they are the largest single contributor to what the authors have estimated as the total provincial degraded area. Lewis (1988) recommended complete rehabilitation for those landings which have the best chance of recovering forest productivity (i.e., those landings located on better sites and soils — Good and Medium sites).

Complete landing rehabilitation involves the following:

1. dispose of slash on winter and summer landings to meet protection, recreation, and aesthetic objectives;
2. ensure landing drainage and prevent access roads from draining onto the landing;
3. spread ash and/or remaining woody and organic debris and recoverable soil (stored during landing construction) over the entire landing;
4. decompact the landing to an average depth of 50-60 cm;
5. seed with an innoculated legume mix appropriate to the biogeoclimatic subzone at a rate of 35 kg/ha, fertilizing at a rate of 200 kg/ha with 20-24-15 (N-P-K); and
6. reforest with coniferous species most tolerant of adverse soil conditions.

Recent experience has shown that successful, total landing rehabilitation should involve all of the above steps if a merchantable crop is to be produced. Lewis also recommends partial landing rehabilitation for landings located on Poor or Low sites and some Medium sites where the adverse properties of soils, surficial deposits, or slopes greatly reduce the chance of success for complete rehabilitation, and where productivity losses are acceptable. The objective of partial rehabilitation is not to restore forest productivity on the landing, but to provide sufficient vegetative cover to minimize erosion, to provide forage for wildlife or domestic stock, and to reduce the adverse visual impacts of the landings. Thus, partial rehabilitation involves steps (1), (2) and (3) noted above, but less intensive seedbed preparation and revegetation efforts. Minimal rehabilitation is recommended for only those very small landings (0.1 ha) on terrain having low to moderate degradation sensitivity and where off-site impacts will not occur (Lewis 1988).

Lewis (1988) further recommends two levels of rehabilitation for skidroads:

1. basic rehabilitation is intended to maintain natural drainage and to minimize erosion; and

2. total rehabilitation is intended to restore forest productivity of severely degraded sites to levels capable of producing trees of merchantable size at rotation, as well as to address erosion control. Basic rehabilitation is suggested for all bladed skid roads and trails with extensive exposure of mineral soil. Total rehabilitation is suggested only for skidroads on clearcuts where deep disturbance is severe and significant productivity reductions are expected.

4.2 Annotated Literature

Andrus, C.W. and H.A. Froehlich. 1983. An evaluation of four implements used to till compacted forest soils in the Pacific Northwest. Oreg. State Univ., For. Res. Lab., Corvallis OR. Res. Bull. 45. 12 p.

The methods currently used in the Pacific Northwest to till compacted forest soils were evaluated. The effectiveness of using rock rippers, tines, brush blades, disk harrows and winged subsoilers was examined over a range of sites. The brush blade loosened only the top 10.2-17.8 cm of soil in primary skid trails where the soil had been compacted to a depth of 30.5 cm. Rock rippers were unable to loosen 55-80% of the compacted soil on 5 different sites. Disk harrows penetrated less than 10.2 cm deep on a moist clayey soil. On the same soil, a winged subsoiler loosened 64% more soil than did the conventional tines (tines spaced 1.37 m, ripping depth equal to 45.7 cm). In a rocky granular soil, the winged subsoiler loosened 35% more soil than did the conventional tine. A three-winged subsoiler was tested. On a dry loam soil, a single pass loosened 80-90% of the compacted soil. On the moist clayey soil, ripping with the three-winged subsoiler loosened 70% of the compacted soil mass within the skid trails. Guidelines are presented for tilling compacted forest soils.

Berg, P.J. 1975. Development in the establishment of second rotation radiata pine at Riverhead Forest. N.Z.J. For. 20: 272-282.

This paper illustrates the success of rehabilitation efforts on compacted cutover land in New Zealand. The clay soil was treated by ripping to depths of 45-60 cm and fertilized with superphosphate. After 3 years, seedling survival on the logging landings went from 69 (control) to 85%. The assessed height increased from 67 to 102 cm, with an increase of 410% since planting, compared to 168% on the non-treated trees.

Berglund, E.R. 1978. Seeding to control erosion along forest roads. Oreg. State Univ., Extens. Serv. Extens. Circ. 885. 19 p.

Grass and legume cover can solve surface erosion problems. Foliage protects the soil surface and reduces the impact of surface water movement. Dense root systems stabilize surface particles. Success can be had with a vegetative cover of 40% or more. An erosion control program by revegetation requires that the climate and soil characteristics and the physical features of the plant materials be considered in selecting species. Adaptability and specific characteristics of common species for erosion control are presented. The seeding rates recommended are computed on the basis of desired seed distribution after application. Cutbanks and fillslopes roughened during construction are ideal seeding sites. Additional stabilization efforts may be necessary on critical slopes. Fertilization is often essential for establishment of adequate ground cover. Recommendations are given for fertilizer formulation, rate of application, and timing and schedule of application. Similar information is given for recommended mulches.

Carr, W.W. 1986a. Assessment of landing rehabilitation activities in the Prince George East Forest District. Contract Rep. B.C Min. For. Lands, Prince George, B.C. Unpubl. 14 p. and appendices.

In 1984, approximately 300 landings in the Prince George East Forest District were “rehabilitated” following standard procedures as established by the Prince George Forest Region. Following slash disposal, the landings were ripped using a rock ripper mounted on a D-8 tractor and broadcast seeded with a grass-legume mix. However, the study found the rock ripper to be ineffective, with a maximum depth of ripping of approximately 17 cm rather than the desired 30 cm. The soil also was found to resettle into a dense, structureless mass. The nutrient levels were lower on the landings: at Craze Creek, N levels at 724 kg/ha as compared to 3316 kg/ha off-landing, P at 24 kg/ha on the landing, 133 off, and K 85 kg/ha on the landing, 305 off. These levels do not meet the minimum levels for commercial pine establishment.

Carr, W.W. 1986b. Evaluation of ripping effectiveness of a winged subsoiler for soil decompaction in the Prince George Forest District. B.C. Min. For. Lands, Prince George, B.C. Unpubl. Rep. 10 p.

Soil tillage with the winged subsoiler was effective in reducing soil density and ripping to an acceptable depth. The overall profile density was reduced by 7, 8 and 17% on the three landings, to below the density range of 1300-1400 kg/m^3, considered to be the threshold density for impeding vegetation growth. The average depth of ripping was 41 cm.

Carr, W.W. 1986d. Soil reconstruction on landing areas in the Mackenzie Forest District-Lakeland Mills Ltd. Unpubl. Interim Report. B.C. Min. For. Lands, Prince George, B.C. 10 p.

This report discusses the rehabilitation progress on landings in the MacKenzie Forest District. The landings were treated by tilling with a winged subsoiler pulled by a D-7 tractor. The maximum depth of ripping, average depth, and degree of profile shatter (%) are basically the same for both topsoil and non-topsoil treatments within each cutblock. On the first site (29000 Road) the maximum depth of ripping was 50 cm (topsoil) and 40 cm (no topsoil), the average depth of ripping was 37 cm and 28 cm, while the profile shatter was 123% and 93%. The average resulting rooting depth was 38 cm and 34 cm. In the 0-30 cm range, the bulk density was reduced from 1750 kg/m^3 to 1240 kg/m^3 in the tilled landing with topsoil, and 1615 kg/m^3 without (1350 kg/m^3 on the off-landing). On the second site (6200 Road), maximum depth of ripping was 39 cm (topsoil) and 32 cm (no topsoil), with an average depth of 21 cm and 22 cm. Profile shatter was 70% and 73%, with an average resulting rooting depth of 24 cm and 28 cm. In the 0-30 cm depth range, the landing bulk density was 1720 kg/m^3 and was reduced to 1390 kg/m^3 on the tilled landing with topsoil, and 1560 kg/m^3 without (off-landing at 1185 kg/m^3). The topsoil was also effective in enhancing nutrient levels, so topsoil stockpiling during construction of landings is an important step in maintaining productivity.

Carr, W.W. 1987a. Restoring productivity on degraded forest soils: two case studies. FRDA Rep. 002. 21 p.

The use of a green fallow as part of a site rehabilitation measure was tested on a coastal forest soil subjected to accelerated erosion, and on an interior site that had been subjected to landing construction. The coastal soil was a compacted, gravelly glacial till with a sandy loam texture. The interior site was a gravelly glaciofluvial deposit with a sandy loam texture. On the coast, substantial enhancement of site nutrient capital occurred within 5 years. Douglas-fir seedlings responded with improved foliar N and K, and a 300% increase in height growth. On the interior site, the decompacted landings were treated with broadcast applications of a legume seed mix and fertilizer. There was an improvement of soil N,P, and K capital of the soil after 2 years, but no change in tree growth.

Carr, W.W. 1988. The rehabilitation of degraded forest soil in British Columbia: an overview. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 197-203.

The rehabilitation of degraded forest soil in B.C. has been the subject of considerable research since the mid-1970's. Significant advances have been made in erosion control so that operational programs can become standard components of forest road building and harvesting operations. While guidelines for landing and skidroad rehabilitation exist and operational procedures are improving, a reduction in the areal extent of soil degradation caused by ground-based logging should remain a high priority to the forestry sector. The objective of rehabilitation should be to recover as much of the soil's original productivity as possible, since full recovery from degradation is doubtful.

Carr, W.W. and T.M. Ballard. 1980. Hydroseeding forest roadsides in British Columbia for erosion control. J. Soil Water Conserv. 35(1): 33-35.

Hydroseeding trials were established on roadside slopes at two locations on southern Vancouver Island. The first site near Shawnigan Lake had an erodible, fine-textured till, and the second site near Cowichan Lake had a very clayey glacial till. Results indicate that a single application of seed and fertilizer was effective as a sequential application. In addition, treatments with or without mulch gave similar results in preventing erosion.

Carr, W.W., R. Frank, and S. Norman. 1985. Effects of soil compaction on forest productivity and an annotated bibliography. Terrasol, Vancouver, B.C. Unpubl. Rep. 14 p.

This report provides a brief overview of the effects of ground-based logging on the physico-chemical and biological properties of forest soils and on soil productivity, followed by a review of pertinent literature. Relevant aspects of productivity, such as seed germination, seedling establishment, root and mycorrhizal development, and tree growth, are reviewed and interpreted. The results of site amelioration trials are also presented. The last section deals with bulk density determination methodology to assist the land manager in assessing the degree of soil compaction occurring in his sites.

Froehlich, H.A. 1984. Mechanical amelioration of adverse physical soil conditions in forestry. *In* Proc. Symp. on Site Productivity of Fast Growing Plantations. IUFRO, Pretoria and Pietermaritzburg, RSA. pp. 507-521.

A wide array of tools for application to forest conditions is discussed in this paper. Most of the corrective measures employing those tools can be grouped into six types: disking, bedding, mounding, ripping/subsoiling, chopping, and furrowing. Research work from each of these types is reviewed and advantages and disadvantages are noted. Nearly all of the research reports show marked improvement in seedling establishment. Improved seedling growth response to the treatment is not always achieved and a good initial response may not persist as long as expected. Many questions remain as to how to obtain the desired soil condition at the lowest cost. The large variation in growth response to the same treatment at different sites highlights the need to carefully match the treatment to the soil problem. Additional research is very much needed to determine effective combinations of mechanical treatments with soil amendments such as organic material, fertilizer and other chemicals.

Froehlich, H.A. and D.H. McNabb. 1984. Minimizing soil compaction in Pacific Northwest forests. *In* Forest soils and treatment impacts. E.L. Stone (editor). Proc. 6th N. Am. For. Soils Conf. Univ. Tennessee, Knoxville, TN. pp. 159-192.

High organic matter content and other inherent properties make Pacific Northwest forest soils generally low in bulk density, high in porosity, and low in strength. As a consequence, these soils are susceptible to compaction by tractive machines, and stand growth may be decreased from 5 to 15%. Natural ameliorative processes do not rapidly loosen compacted soil, and where it remains compacted, stand growth losses are measurable for at least 3 decades. Prohibiting the use of tractive machines on soils most susceptible to compaction, suspending operations above specified soil moisture contents, or requiring the use of low ground pressure machines can effectively minimize the extent of soil compaction impacts. Where compaction has resulted in soil degradation, tillage of these compacted soils with properly designed and used implements can be effective in restoring productivity levels. Reducing the area of compacted soil by designating skid trails may be the most economical means to maintain site productivity in the Pacific Northwest.

Froehlich, H.A., D.W.R. Miles, and R.W. Robbins. 1985. Soil bulk density recovery on compacted skid trails in central Idaho. Soil Sci. Soc. Am. J. 49: 1015-1017.

In west-central Idaho, the bulk densities of soil in major skid trails were compared to those of adjacent undisturbed soil to determine rates of recovery. Five study sites on each of 2 soils, one formed from granitic material and the other from volcanic material, provided 2 chronosequences (five 5-yr periods) of time since logging. Bulk density was measured at 5.1, 15.2 and 30.5 cm depths. The percent increase in bulk density of soil on a skid trail over that on an adjacent undisturbed area was greater in the volcanic than the granitic soil, but recovery rates for the 2 soils were not significantly different. A significant recovery trend was shown for all depths except the 15.2 cm depth on the volcanic site. Except for the surface 5.1 cm of the granitic soil, none of the bulk densities in skid trails had returned to the undisturbed values in the 23 years since logging.

Hatchell, G.E. 1981. Site preparation and fertilizer increase pine growth on soils compacted in logging. South. J. Appl. For. 5(2): 79-83.

Herbicide treatment, disking or bedding alone did not restore the growth potential to compacted soils. However, fertilization (N200, P50, K100) with any of these treatments restored — and with disking, greatly enhanced — height and diameter growth.

Homoky, S.G.J. 1984. Case histories of hydroseeded research test sites. B.C. Min. Forests, Victoria, B.C. Res. Rep. RR84003-HQ. 97 p.

This report summarizes the forest roadside revegetation research of the Research Branch of the B.C. Ministry of Forests, aimed at the control of surface erosion. Assessment results of individual test sites are listed in the form of a permanent record. Successes, limitations, and suggestions for improvement are discussed. This report will benefit field staff by demonstrating the potentials of hydroseeding in roadside erosion control.

Homoky, S.G.J. 1987. Case histories of hydroseeded research test sites: post-1982 period. B.C. Min. For. Lands, Victoria, B.C. Res. Rep. RR87998-HQ. 103 p.

This report updates the results of the forest roadside revegetation research first reported in 1984. Since then, changes have occurred in the physical characteristics and biological performances of these plots. This report covers the period 1982-1986 and (1) documents the successional development or regression of the established plant cover; (2) records the advance of indigenous species; (3) suggests improved selection of materials according to the particular environment; (4) advises on the proper timing of seeding application during the growing season; (5) demonstrates the usefulness of vegetation maintenance; and (6) points out other relevant features that might further enhance or endanger slope stability and environmental protection.

Marchant, C.J. and J. Sherlock. 1984. A guide to selection and propagation of some native woody species for land rehabilitation in British Columbia. A user guide for forestry personnel. B.C. Min. For., Victoria, B.C. Res. Rep. RR84007-HQ. 117 p.

This preliminary guide reflects the need for research into the uses of native woody plants in land reclamation and rehabilitation, and into the propagation methodology of woody deciduous native species. Some of this research has now been carried out for some 26 native species in B.C. The guide outlines the propagation methods shown so far to produce reasonable numbers of propagules for use in field outplanting. The guide also touches on the various eco-physical aspects of disturbed land, and on the criteria to be considered in the selection of appropriate woody species for use in land reclamation techniques on various soils and in differing macro- and microclimates. The information is intended mainly for plant nursery technicians responsible for shrub propagation, and for field personnel involved in the identification and collection of seed and cuttings from native woody species to be used in land rehabilitation. Some of the information will also interest the road engineer who wishes to incorporate revegetation methods into construction plans.

McLeod, A.J. and W. W. Carr. 1986. Rehabilitation of degraded forest soil in the Prince George Forest Region. *In* Land rehabilitation: policy, planning systems and operational programs. 11th Annual Meeting, CLRA, Univ. B.C., Vancouver, B.C.

This paper outlines seven operating procedures for the rehabilitation of degraded forest in Prince George. The seven procedures are:

1. approval for cutting permit;
2. limiting the number and size of landings (not normally to exceed 3.5% of the total area of the cutblock);
3. location (landings shall be a minimum of 40 m from all cutblock edges, immature timber, lakes, swamps, streams and open, natural range);
4 construction of landings;
5 operations (concerning the cull pile);
6. slash disposal (burning of the cull pile on the landing); and
7. rehabilitation of the landing using a winged subsoiler and reseeding with legumes if full rehabilitation is warranted.

5 METHODOLOGIES FOR SITE ASSESSMENT

5.1 Summary

Four main methods have been used to survey and assess the level of soil disturbance on harvested blocks:

1. aerial photographs and planimetry;
2. the point-transect method;
3. the line-intercept technique; and
4. ground traverse method.

5.1.1. Aerial photography

Utzig and Herring (1975) used aerial photographs to measure the amount of site disturbance on clearcuts. Using 1:15 840 scale photographs, they planimetered landings, measured lengths of skidroads and haulroads, and calculated the area of the roads by multiplying measured lengths by 5 m for skidroads and 8 m for haulroads. Measuring a number of road widths and even undertaking a transect survey directly on the photograph would be possible if larger scale photographs (e.g., 1:5000) were used. One possible way of accomplishing this would be to plot the transect lines directly on the photographs and then survey the lines with an ADDO-X type of apparatus. On steep slopes (>30%), for example, one would be able to estimate the amount of deep disturbance for conventional skidroads and haulroads by using average widths (e.g., 8.1 for conventional skidroads [McMorland 1980, Smith and Wass 1976]) and multiplying by a disturbance factor (66% for skidroads and 85% for haulroads [Smith and Wass 1976]) to arrive at a width which represents the amount of deep disturbance (e.g., 8.1 m x 0.66 = 5.3 m for skidroads). Estimates for the amount of deep disturbance from landings would best be derived by planimetering the landings separately.

5.1.2 Point-transect method

In this ground-based method, transects are laid generally at or close to a right angle to the site contours, and specific points are described along the transects at prescribed intervals. A 3-m interval has commonly been used to ensure that all skidroads are sampled. The initial step in this method is stratification of cutblocks and establishment of a base line along one edge (lower edge if on a slope) of the harvested area. The starting points of the transects should be about 100 m apart. For routine or preliminary surveys, such a systematic location of starting points is suitable.

Using a random method of starting point location as described by Bloomberg *et al*. (1980a) permits a more statistically valid assessment of variation and adequacy of the sampling intensity. Transects can be aligned in a zigzag pattern across the clearcuts if necessary to achieve the necessary sampling intensity (Krag *et al*. 1986). To locate sampling points, a rod is dropped onto the ground surface using the specific chain mark as a guide. The condition of the soil surface at that exact point is described. If one is carrying out a survey of deep disturbance caused by landings, skidroads, and haulroads, for example, the description categories could be limited to ‘‘undisturbed’’ (including slight disturbance, i.e., disturbance <25 cm in depth) and ‘‘deep skidroad,’’ ‘‘deep haulroad’’ and ‘‘deep landing’’ disturbance (>25 cm in depth). Also, if the information is known, haulroads can be separated as permanent or temporary.

Given the sporadic distribution of landings, taking direct measurements of the landing dimensions would be a useful check on the results from the transect survey. Sidecast deposits of less than 25 cm in depth can be estimated with the insertion of the point-transect rod. The depth of gouges less than 25 cm has to be gauged in comparison to surrounding undisturbed surfaces. The cover (%) of each disturbance category is determined on the basis of the number of points encountered in each category and the total number of points sampled in the survey.

5.1.3 Line-intercept method

This technique involves running out a line, as in the point-intercept method, and recording only the disturbance categories of interest (Bloomberg *et al*. 1980a; Smith and Wass 1976). As disturbances are encountered along the line, their beginning and end points are recorded with the appropriate classification. No observations are made between spots. The total length of each disturbed category is determined as a proportion (%) of the total length of line surveyed. Some other similarities with the point-intercept system are: random or systematic location of line starting points; if systematic, recommended interval between line starting points is 100 m; establishment of a base line; direct measurement of landings; measurement of depths of disturbance. For a simple survey of deep disturbance caused by road construction, the line-intercept system would be more efficient than the point-intercept method, but the latter method is more suitable for inventorying a wider range of disturbance classes and systematic collection of other types of data (e.g., slash cover, humus type and condition, and bedrock exposure).

Howes *et al*. (1983) have provided a slightly different approach to the line-intercept method. In their system, the layout of sampling points consists of a predetermined, systematic square grid. The dimensions of the grid are determined by the size of area being sampled and a calculated sample size. Grid orientation is random and grid intersections are the starting points for line transects, which are generally 30 m long. Orientation of each line transect is also randomly assigned. Grid spacing and distribution of points provide complete coverage of the area to be sampled.

5.1.4. Ground traverse method

This method first involves delineating soil disturbance sampling units (should be larger than 5 ha and should be visually characterized by a relatively homogeneous degree of disturbance) and calculating the total ‘‘plan view’’ sample unit area from maps or air photos of known scale. The field measurements include: the entire length of all bladed skidroads on the sample unit (measured by hipchain); full width (slope-distance) of skidroads every 200 m at the most (use hipchain or telescoping height pole to measure from edge of the cutslope to the bottom edge of the fillslope); upslope and downslope readings to adjust measured ‘‘plan view’’ area to ‘‘slope area’’ for the sample unit; and area of all landings by traversing each landing with a hipchain and silva compass (from top edge of the cutbank to the bottom edge of the fillslope) (Still and Thompson 1987).

This method is likely to give more accurate estimates of soil disturbance on bladed structures than most sampling systems. It is simple and practical, and office computation is easy to carry out. Its disadvantages are that it likely requires more field time than a statistically sound sampling design would, and it is not practical to use on areas where bladed skid trails do not occur.

5.2 Annotated Literature

Adams, P.W. 1979. Recognizing and measuring soil compaction. USDA For. Serv., North. Region. Soil Air & Water Notes. 9 p.

This is a description of methods for measuring soil bulk density, such as soil cores, excavation, soil clods, and radiation.

Bloomberg, W.J., P.M. Cumberbirch, and G.W. Wallis. 1980a.

A ground-survey method for estimating loss caused by *Phellinus weirii* root rot. I. Development of survey design. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-R-3. 23 p.

The ground survey method described here can be applied to determining the extent of soil disturbance in an area. A transect line sampling system is used, with a grid system to measure the ratio of disturbed soil to undisturbed soil. The extent of the disturbed soil can be further measured by a rectangular method, radial method, linear method, or regression method, the procedures for which are detailed in the report.

Bloomberg, W.J., P.M. Cumberbirch, and G.W. Wallis. 1980b. A ground survey method for estimating loss caused by *Phellinus weirii* root rot. II. Survey procedures and data analysis. Can. For. Ser., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-R-4. 44 p.

This report outlines procedures for designing a ground survey applicable to soil degradation analysis. Office procedures, such as the selection of baseline location and number, location and width of transect lines, as well as field procedures are outlined. Methods for recording, analyzing and summarizing field data are described.

Howes, S.W., J.W. Hazard, and J.M. Geist. 1983. Guidelines for sampling some physical conditions of surface soils. USDA For. Serv., Pac. NW Region, Range Watershed Manage., Portland, OR. R6-RMW-146-1983. 34 p.

Procedures are provided for sampling and estimating the extent of some physical conditions of surface soils caused by forest management activities. Calculations and statistical methods enabling users to make quantitative statements of the precision of estimates are described.

Krag, R.K., K. Higginbotham, and R. Rothwell. 1986. Logging and soil disturbance in southeast British Columbia. Can. J. For. Res. 16: 1345-1354.

Methods used for determining percent soil disturbance in the cutblock area are based on Smith and Wass (1976). Using exposed mineral soil as an index of soil disturbance, point samples were taken along transects angled across contours. Transects were aligned in a zigzag pattern. Sample points were established at 2 m intervals with 15-20 points per hectare as a goal. A minimum of 400, and preferably between 700 and 900, points was sampled on each clearcut.

Smith, R.B. and E.F. Wass. 1976. Soil disturbance, vegetative cover and regeneration on clearcuts in the Nelson Forest District, British Columbia. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-X-151. 37 p.

This survey used line transects with both point and mil-acre (0.0004 ha) plot observations made at 3-m intervals. The start of the transect was usually located at the bottom of the clearcut and a direction was selected so that the line angled slightly off from a right-angle crossing of the contours. Points and plot centers were located by means of a nylon chain equipped with metal tabs. When the chain was located above the ground surface, a stick (1.14 m long) was used as a plumb to establish the point directly under the chain marker and to mark the radii of the mil-acre plots. Point observations were made for the type and cause of soil disturbance, other surface conditions, vegetation species and cover, and tree regeneration.

Smith, R.B. and E.F. Wass. 1985a. Changes in soil surface conditions at Marl Creek root-rot control site. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Unpubl. Rep. 11 p.

Methods for assessing site disturbance include using a transect survey of 3-m intervals. Soil strength was measured for each major disturbance type using a cone penetrometer. Bulk density was measured by means of a sand density apparatus at depths of 0-10 cm and 10-20 cm.

Still, G. and S. Thompson. 1987. Evaluation of soil disturbance in the Golden Forest District. B.C. Min. For. Lands, Nelson, B.C. Unpubl. Working Plan, EP 1022. 12 pp.

The sampling methods described in this working plan have been used successfully on 3 cutblocks by the Nelson Region Research staff. Skidroads, secondary roads, and landings are measured separately. An estimate of the area disturbed by roads is found by hipchaining the total length of secondary and skidroads and multiplying by the measured mean road widths. For landings, the perimeter is mapped and the area determined by dot gridding.

6 SENSITIVITY RATING SYSTEMS

6.1 Summary

Because of the dearth of appropriate research data, not many comprehensive sensitivity rating systems have been developed. Individual sensitivity rating criteria (e.g., compaction hazard, erosion hazard, mass wasting hazard) (Mitchell 1984) can be used, but the level of complexity and integration required for the full development of rating systems has not yet been achieved. There has been an increase in the understanding of the factors determining degradation sensitivity, but the effects of these factors have not been sufficiently quantified. The usual procedure has been to develop standards from available research results and apply them to subjectively established classes of degradation sensitivity.

Lewis (1988) reviews two approaches to rating degradation sensitivity. The first involves directly evaluating individual hazards of slope failure, surface erosion, soil displacement, and compaction; integrating these with a few additional site factors; and determining a sensitivity rating. This routine is process-oriented and time-demanding, yielding an evaluation of the level of degradation and an identification of the anticipated degradation process. The second method is not process-oriented but depends completely on the direct evaluation of a number of individual site factors (e.g., slope; soil depth; presence of seepage water, water courses or gullies; soil texture; soil moisture; and regional climate). This approach is less time-consuming and less rigorous (and thus not as accurate and as precise) as the first method, but it is appropriate for evaluating the lower sensitivity ratings.

6.1.1 Surface erosion hazard rating

There are a number of surface erosion hazard rating systems currently being used for forested lands, ranging from the empirical (Universal Soil Loss Equation) to the diagnostic (expert systems). The empirical methods have been beset with problems, such as high variability of results and difficulty of interpreting results from harvested forest sites, and have not been very successfully applied to forestry concerns. The diagnostic approach involves identifying important site factors and deriving interpretations using an algorithm developed by forest science experts. Such algorithms rely on a more limited, often qualitative, data base than do the empirical methods, but the user gains a better understanding of the problem by using the interpretive process.

An example of a broad algorithm or key is that developed and used in the Kamloops Forest Region (Mitchell 1984). The following factors are included: mean annual precipitation, slope gradient (%), depth of soil to a restricting layer, surface soil detachability (inferred from soil texture or aggregate structure), subsoil permeability (the rate of water movement in the subsoil as inferred from soil texture and coarse fragment content), and coarse fragment content (%). Each of these factors is given a numerical rating, and the surface erosion hazard rating (low, moderate, high or extreme) is determined by adding the numerical values of the contributing environmental factors. The information needed for this key is qualitative, thus requiring less field or laboratory time, an important consideration when selecting a system for operational application.

Carr *et al*. (1988) have produced a new key for predicting surface soil erosion hazard by modifying the Mitchell (1984) key to include greater emphasis on rainfall and topography factors, that is, to bring it more in line with the theory behind the Universal Soil Loss Equation. The climate factor now includes a rainfall factor (R) which predicts rainfall intensity and the total kinetic energy of regional precipitation. The ‘‘R’’ value presents a more realistic reading of the erosive energies involved in rainfall and, on a broad level, correlates well with the biogeoclimatic classification of B.C.

The topography factor has been split into two components: slope gradient and slope uniformity/lengths. Slope uniformity has been defined as ‘‘broken’’ (benched or undulating) or ‘‘uniform’’ (smooth and straight), while length of slope is considered ‘‘short’’ (150 m or less) or ‘long’ (>150 m). The three factors in the soil component (depth to restricting layer, subsoil permeability, and surface soil detachability) combine to provide an indication of the potential for surface soil movement. The final determination of erosion hazard class is a summation of the numerical values given each environmental factor: the range of values is 3 - 12 for both climate components; 2 - 8 for slope gradient, 1 - 4 for slope length/uniformity; 1 - 4 for depth to restricting layer; 1 - 4 for surface soil detachability; and 0.5 - 2 for both texture and coarse fragment content (subsoil permeability). The aggregate totals indicate the hazard rating: low - <20, moderate - 20-24, high - 25-29, and extreme ->29.

6.1.2 Compaction hazard rating

Butt and Rollerson (1988) reviewed a number of soil properties which have been proposed as important factors which may have predictive value for compaction: texture, soil strength, soil moisture, initial bulk density, level of optimum compaction, and compression index. These authors concluded that no method of predicting compaction can actually do so with any degree of certainty because of variability in site conditions, weather and operational procedures. Anticipation of soil damage is now based on broad perceptions of compaction susceptibility. For example, moist fine-textured soils are widely believed to compact to a greater extent, under a given stress, than well-drained coarse soils.

While recognizing some of these difficulties in reliable compaction hazard prediction, Carr *et al*. (1988) have proposed an index for assessing soil compaction based on the relative compactability under moist conditions for a given soil texture (or particle size) and coarse fragment content, with an accompanying list of modifiers (i.e., site factors that reflect operating conditions). The relative sensitivity to compaction is based on the maximum dry density of the soil, which rates the soil's relative degree of compactability. This texture density rating can be modified by drainage and permeability characteristics to include water and air exchange considerations. The site modifying factors include soil moisture, snowpack, and frozen soil and surface condition (degree of disturbance). These modifiers do affect the ultimate level of compaction resulting from forestry activities and can be used by the forest manager to plan and schedule harvesting and renewal operations better.

6.1.3 Mass wasting hazard rating

Mitchell (1984) has also presented keys for assessing cutslope stability hazard in the Kamloops Forest Region. These keys address two components of cutslope stability: mantle failure hazard and slough failure hazard. Mantle failure is the slippage or slumping of the soil mantle and is usually associated with saturated soil moisture conditions. The environmental factors assessed are: mean annual precipitation, moisture regime (hygrotope), slope gradient (%), cohesiveness of soil material (inferred from texture and coarse fragment content), depth to restricting layer, and presence or absence of existing mantle failures. Mantle failure hazard classes are Stable, Moderately Stable, or Unstable. Slough failure is the surface ravelling of a cutslope due to gravity following excavation and is usually associated with dry soil conditions. The environmental factors assessed are: aggregate stability of soil material (inferred from texture and coarse fragment content), depth to restricting layer, and susceptibility to frost action. Slough failure hazard classes are Low, Moderate or High. The cutslope stability hazard ratings are determined by adding the numerical values assigned to the contributing factors. These ratings apply to cutslopes that are at least 1 m in height.

A terrain evaluation method for predicting post-logging landslide activity has been presented by Howes (1987) and Howes and Sondheim (1988). The method is based on the analysis and integration of base data obtained from a landslide inventory and a terrain (surficial geology) mapping program, and is considered to be more objective and quantitative than previous approaches used in B.C. It involves 4 steps: 1) defining homogenous areas, referred to as terrain polygons, with respect to their surficial geology; 2) analysis of landslide site data to identify factors influencing landslides in clearcuts; 3) defining a set of terrain classes based on these factors such that each polygon can be assigned to only one class; and 4) grouping the classes into 4 stability ratings based on the ratio of the number of landslides in clearcuts to the hectares of clearcut.

6.1.4 Degradation sensitivity

Degradation sensitivity is simply the susceptibility of a site to degradation. This sensitivity is inherently determined by site characteristics, such as slope gradient, seepage presence, soil texture, soil depth, soil moisture, humus form development and thickness, Ae or Ah horizon development, and climate. Data on these characterisitics are usually collected during the pre-harvest assessment process. These data can be used to determine hazard ratings for erosion, slope stability, and compaction, for example; and sensitivity ratings can be determined using the appropriate algorithms.

Based on available information, only rough approximations of degradation sensitivity can be made at present. Lewis (1988) has used the approach taken by Mitchell (1984) to list criteria for determining site sensitivity classes for B.C.'s forest soils. This four-class system integrates the limited existing information from B.C. and Pacific Northwest soils research with the knowledge and expertise of practicing soil scientists and foresters in B.C.

This rating system is as follows:

1. low degradation sensitivity - slopes <30%: deep soils; low slope failure hazard; low to moderate surface erosion and compaction hazards; lacking seepage; slopes 30-45%: deep soils; low slope failure hazard; low surface erosion and compaction hazards; lacking seepage;
2. moderate degradation sensitivity - slopes 0-45%: deep soils; low to moderate hazards for slope failure, erosion and compaction; lacking seepage;
3. high degradation sensitivity - slopes >60%: deep soils; low to moderate slope failure hazard or moderate to high surface erosion hazard; slopes 46-60%: deep soils; moderate slope failure hazard or high surface erosion hazard; slopes 30-45%: shallow soils; high slope failure hazard or high to extreme surface erosion hazard; slopes 30-45%: seepage and frequent water courses or gullies; slopes 30-45%: high compaction hazard; and
4. extreme degradation sensitivity - slopes >46%: shallow soils; existing mantle failures; presence of seepage, frequent water courses or frequent gullies, or high slope failure hazard or extreme surface erosion hazard.

6.1.5 Operating standards

The determination of degradation sensitivity criteria can be used to derive standards for determining operational limits to acceptable disturbance. Standards, to be meaningful and implemented, should emphasize observable and measurable soil characteristics which field personnel can easily use to monitor the impacts of the harvesting activities. Site sensitivity guidelines are presently being developed using biogeoclimatic and site variables from the zones and subzones in each Forest Region. These guidelines will be formulated into standards for acceptable disturbance levels (as done in Mitchell [1984]). At the present time, the standard for the areal extent of acceptable deep disturbance (>25 cm) is a point of some discussion. Lewis (1988) proposed the following:

Sensitivity class	Deep disturbance (%)	
	No fireguard	Fireguard
Low	10 (12)*	13 (15)
Moderate	10 (12)	13 (15)
High	6 (6)	8 (8)
Extreme	3 (3)	3 (4)

* The figures listed in the parentheses are those standards being proposed in the *Reduction of Productivity Losses from Logging Operations* (B.C. Ministry of Forests, Timber Management Branch) and are those adapted from Mitchell 1984.

The Technical Advisory Committee (TAC) of the Interior Forest Harvesting Committee (IFHC) recently submitted the following guidelines with respect to total allowable soil disturbance:

Sensitivity rating	Percent total allowable soil disturbance
Very high	4
High	9
Moderate	19
Low	19

These percentages are based on the sum of the areas of unapproved haulroads, landings, backspar trails, skidroads, and heavily used skid trails.

The IFHC TAC also included the following guidelines:

1. Unapproved haulroads and roads associated with access logging will be included in the soil disturbance measurements for the cutblocks. The cumulative total area of disturbance related to landings and to the widening of roads for log handling purposes will not exceed 4% of the total cutblock area.
2. The locations and approximate dimensions of landings will be identified on the harvesting plan or map and included with the cutting permit application. Widening of haulroads beyond the standard width to accommodate roadside logging systems will be considered as disturbance if the widened areas have been bladed or heavily used. The area occupied by backspar trails is included as disturbance under these guidelines and will not exceed 3-5% of the total cutblock area. Where possible, backspar trails should serve as fire guards.
3. A reasonable approximation of skidroad location and density must be made at the pre-harvest stage and, depending on local conditions, may be refined as field planning becomes more definite. Skidroad locations must be identified on harvesting plans or maps before issuance of the cutting permit, and laid out on the ground (including adjustments to on-site conditions) before construction begins.

Howes (1988) states that the acceptable soil disturbance standard for the Pacific Northwest Region of the USDA Forest Service is 20%. It is important to note, however, that what the U. S. Forest Service considers detrimental displacement would be called slight or shallow disturbance in B.C. and, as such, would not be considered detrimental here.

6.2 Annotated Literature

Butt, G. and T. Rollerson. 1988. Prediction of forest soil compaction. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 153-166.

The accurate prediction of forest soil compaction is seen as a useful tool in forest management, but the consequences of inaccurate prediction can be serious. Different methods of identifying compactible soils are reviewed here. Predictive models in the literature have incorporated various soil factors, including soil texture, soil moisture, soil strength, initial bulk density, optimum compaction, and compression index. Existing models have limited applicability for one reason or another. At the present time, the identification of soils susceptible to compaction is carried out in a subjective and inconsistent fashion. This makes it difficult to know when to apply alternative methods for minimizing soil compaction.

Carr, W.W., W.R. Mitchell, and W.J. Watt. 1988. Basic soil interpretations for pre-harvest silviculture planning: surface soil erosion, soil compaction. Terrasol, Vancouver, B.C. Unpubl. Rep. 34 p.

Guidelines were developed for surface soil erosion and soil compaction. They are based on existing models but have been modified to reflect recent research and available data bases. The soil erosion hazard index is a modification of the system used by the Kamloops Forest Region which is based on the U.S.Forest Service Region 6 method. The index for assessing soil compaction is based on the relative compactibility under moist conditions for a given soil texture (or particle size), and coarse fragment content with a list of modifying site factors that reflect operating conditions. In this manner, basic decisions regarding harvesting equipment and season can be made.

Chamberlin, T.W. and W.W. Jeffrey. 1968. Soil movement-water quality deterioration associated with timber harvesting in the West Kootenay area. Univ. B.C., Fac. For., Vancouver, B.C. Misc. Publ. 4.

This study set out to fulfill three objectives. First, it examined the major causes of soil movement and water quality deterioration related to logging in the West Kootenay area. Second, it predicted the erosion hazard for different surficial deposits to provide a relative rating useful to land managers. Third, it considered the quantitative soil stability measures which are applicable to the prediction of erosion hazards.

Daddow, R.L. and G.E. Warrington. 1983b. The influence of soil texture on growth-limiting soil bulk densities. *In* New forests for a changing world. Proc. 1983 SAF Nat. Conv., Portland, OR. pp. 252-256.

A quantitative relationship between growth-limiting soil bulk density and soil texture was developed to use in evaluating the impact of soil compaction on plant root growth. Growth-limiting bulk density represents the threshold condition where resistance to root penetration is so high that root growth is stopped. Twenty-one data sets and a modified Gupta-Larsen bulk density model were used to develop the relationship.

Halverson, H.G. and R.P. Zisa. 1982. Measuring the response of conifer seedlings to soil compaction stress. USDA For. Serv., NE For. Exp. Sta. Res. Paper NE-509. 6 p.

Seedling growth response to several levels of soil compaction showed that root penetration depth was best correlated with soil compaction. Shoot biomass, root biomass, root elongation, and seedling height were not well correlated with compaction.

Howes, D.E. 1987. A terrain evaluation method for predicting terrain susceptible to post-logging landslide activity. A case study from the southern Coast Mountains of British Columbia. B.C. Min. Environ. Parks, Victoria, B.C. MOEP Tech. Rep. 28. 38 p.

The terrain evaluation method presented for landslide prediction is considered to be more objective and quantitative than past terrain evaluations used in B.C. Terrain with the highest clearcut landslide rates within the study area included till or till/colluvial mantles on slopes $>33°$ and colluvial mantles on slopes $>36°$ that are dissected by gullies, and escarpments of unconsolidated sediments with slopes $>33°$. The clearcut landslide rate varies from 0.83 to 6.6 times the natural rate on different terrain types and the 1963-1981 clearcut landslide rate is 1.72 times the 1953-1962 rate. In contrast, the natural landslide rate has essentially remained constant since 1940. The difference between the clearcut and natural landslide rates over this period suggests that the removal of forest cover has strongly influenced the clearcut rate by increased water inputs and soil moisture changes and/or the reduction of root reinforcement aggravated by increasingly wetter conditions from 1953 to 1981. An estimated volume of 1.36×10^6 m^3 of soil was eroded between 1950 and 1981 by rapid mass movements (81% of the total) and slumps (19% of the total) from the hillslopes, about 88% of which entered the stream system. The contribution of natural and clearcut landslides to this total varied over time. Natural landslides were the major contributor from 1950-1962, while clearcut slides became the dominant contributor from 1963 to 1981.

Howes, S.W. 1988. Consideration of soil productivity during forest management activities: the USDA Forest Service approach in the Pacific Northwest. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 185-190.

This paper describes the direction and processes followed by U. S. Forest Service land managers to ensure that soil productivity is not degraded to unacceptable levels by forest management activities. Included are discussions of legal and agency direction concerning soil productivity protection, the risk assessment process, management prescription development, contractual considerations, and monitoring and assessment of management activities.

Based on available research results, standards for determining detrimental compaction, puddling, displacement, and severely burned soils were developed. These standards are as follows: 1) detrimental compaction - volcanic ash and pumice soils, an increase in soil bulk density of 20% or more over the undisturbed level; all other soils, an increase in soil bulk density of 15% or more over the undisturbed level, and/or a macropore space reduction of 50% or more, and/or a reduction below the 15% level as measured by an air permeameter; 2) puddling - when soil is molded and depth of rutting reaches 15 cm or more; 3) detrimental displacement - removal of more than 50% of the forest floor or upper mineral soil horizons from an area of 10 m^2 or more which is at least 1.5 m in width; 4) severely burned - top layer of mineral soil has been significantly changed in colour, usually to red, and the next 1.25 cm blackened from charring by heat conducted through the top layer; and 5) areal extent of soil damage - the total area of all detrimental soil conditions following management activities should not exceed 20% of the area to which these activities are applied.

It appears that the issuance of the policy and standards for soil resource protection has been a major factor in encouraging practices which maintain or improve both short- and long-term site productivity. The soil productivity standards were judged to be reasonable and appropriate based on current knowledge of factors affecting soil productivity and site quality.

Interior Forest Harvesting Committee - Technical Advisory Committee. 1989. Interim harvesting guidelines for the interior of B.C. Mimeo. 5 p.

These guidelines are aimed at controlling the occurrence of bladed structures and heavily travelled skid trails, emphasizing pre-harvest planning as the primary step in doing so. These guidelines apply to harvesting-related disturbance only.

Depending on site sensitivity, bladed skidroads and heavily used skid trails will not exceed 15% of the total cutblock area. On very highly sensitive and high sensitive sites, **total disturbance** cannot exceed 4 and 9%, respectively. Thus, the allowable amount attributable to bladed skidroads and heavily used skid trails is reduced accordingly.

Krag, R.K. 1980. A method to estimate risk of soil erosion to logging sites in the Kootenay area of B.C. FERIC Tech. Rep. TR-21. 55 p.

A system is presented for assessing the risk to a forest site of erosion from road building and logging. It proposes a site classification system to supplement the "Handbook for Ground Skidding and Road Building" in the Kootenay area of B.C., by providing procedures for site-specific inspections. To apply the classification system, the user must estimate slope, soil texture, particle size distribution, soil depth, and site moisture regime within the proposed cutting area. The criteria based on these site variables are presented to identify the risks of surface erosion and slope failures.

Lewis, T. 1988. Guidelines for timber harvesting prescriptions for interior sites of various degradation sensitivities. Timber Harvesting Methods Committee, B.C. Min. For. Lands, Victoria, B.C. Unpubl. Rep. 65 p.

This report proposes two approaches for objectively assessing the risk of degradation during harvesting — a hazard approach and a site factor approach — believing that to avoid unnecessary degradation requires a sound assessment of risk prior to planning an operation. Such as assessment fits very well into the now established pre-harvest process, involving only marginal increases in data requirements from that already collected. Suggestions and recommendations for modifications to standard logging practices, on a phase by phase basis, are included to aid the formulation of prescriptions that are tailored to suit differing levels of degradation sensitivity. Negative impacts can be minimized if prescriptions are modified to fit the landscape (which can be interpreted as a mosaic of treatment units each having an intrinsic sensitivity to timber harvesting). Although a range of site rehabilitation options is presented, the report stresses that avoidance of degradation is usually both simpler and less costly than rehabilitation, especially since the long-term effectiveness of some rehabilitation techniques is still uncertain.

McNabb, D.H. and H.A. Froehlich. 1983. Conceptual model for predicting forest productivity losses from soil compaction. *In* New forests for a changing world. Proc. 1983 SAF Nat. Conv., Portland, OR. pp. 261-265.

A simple, conceptual model for predicting forest productivity losses from soil compaction was developed for the Pacific Northwest. Once compacted, most forest soils in the Pacific Northwest are expected to remain compacted and forest growth affected for several decades. Managers should mininize changes in soil properties caused by tractive machines, decrease the area over which the machines operate, or till the soil after it is compacted.

Mitchell, W.R. 1984. Interpretations for timber and silvicultural management in the Kamloops Forest Region. *In* Proc. Soil Management Implications in the Kamloops Forest Region. Min. For., Kamloops, B.C. Unpubl. Rep. 43 p.

This working document outlines the steps necessary to make environmentally sound forest management decisions. These include:

1. classifying and mapping sites (ecosystems or soils);
2. understanding the relationships of forest management to site characteristics;
3. based on the interpretations developed from the data collected in steps 1 and 2, being aware of the site capabilities and sensitivities to management;
4. developing management interpretations or recommendations; and
5. implementing management decisions considering the management objectives and economic feasibility.

The key to the success of this decision-making process is the pre-harvest prescription development program of the B.C. Ministry of Forests.

Niehoff, J. 1984. Technical guide to determine potential soil damage by prescribed burning and wildfire. Unpubl. Rep.

This is a rating guide designed to predict the effects of prescribed burning and wildfire on nitrogen mineralization rates and soil productivity potential. It is designed to identify the high risk soils and conditions under which severe soil damage may occur when exposed to fire. The guide was designed for a broad range of soil types and productivity potentials located in the Idaho Panhandle National Forests, where most of the soils are covered by a blanket of volcanic ash.

Paeth, R.C., M.E. Harward, e.g., Knox, and C.T. Dyrness. 1971. Factors affecting mass movement of four soils in the western Cascades of Oregon. Proc. Soil Sci. Soc. Am. 35: 943-947.

Four soils in the Western Cascades of Oregon were studied to determine their relationship to slope stability. Soils prone to slope failure were characterized by high amounts of smectite clay, absence of kaolin, and moderate amounts of free iron oxides. The more stable soils contained kaolin, more chlorite and chlorite intergrades, less smectite, and higher amounts of free iron oxides. Colour of the soils and of their source rocks was correlated to landscape stability. Areas with tuff and breccia substratum were the site of 93.6% of mass movements even though only 37.2% of the area consisted of these rocks. Of these mass movements, 63.8% occurred on greenish tuff and breccia, which made up 8% of the forest area; and 29.8% occurred on yellowish and reddish tuff and breccia, which made up 29.2% of the forest area.

Rice, R.M. and P.D. Gradek. 1984. Limits on the usefulness of erosion - hazard ratings: experiences in northwestern California. Can. J. For. Res. 14: 559-564.

To improve the erosion-hazard rating procedure, separate estimating equations were used for different situations. Ratings were partitioned according to yarding method, erosional process, and both yarding method and erosional process. A single unified erosion hazard rating procedure is the most practical way of predicting logging-related erosion.

Schroeder, W.L. and D.N. Swanston. 1987. Application of geotechnical data to resource planning in southeast Alaska. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland, OR. Gen. Tech. Rep. PNW-198. 22 p.

Geotechnical information was used to quantify surficial materials. This revealed consistent diagnostic characteristics useful to evaluate landslide risk and subgrade material stability before timber harvesting and road construction. Shear strength data are grouped by soil series (using the Unified Soil Classification system) and by geologic origin. Such groupings allow the selection of strength parameters for slope and subgrade stability, analyses based on existing knowledge of the terrain and on available inventory data.

Sidle, R.C. and D.M. Drlica. 1981. Soil compaction from logging with a low-ground-presure skidder in the Oregon Coast Ranges. Soil Sci. Soc. Am. J. 45: 1219-1224.

The effect of a low-ground-pressure skidder (FMC) on the compaction of a clay loam soil was examined. An increase in the bulk density of the soil on the skid trails was highly correlated to the number of turns with the skidder. The surface 15 cm of the soil was impacted more by uphill than by downhill yarding. Downhill skid trails with 3 or fewer turns, had a less than 10% increase in bulk density. At the 7.5 cm depth, 9 turns increased bulk density approximately 25 and 45% for downhill and uphill yarding, respectively. The levels of compaction were compared to engineering compaction test standards, to see if the laboratory test could be used to estimate potential soil compaction. The modified 10-blow Proctor tests slightly overestimated the increase of bulk density on high-use uphill skid trails. The 15 and 20-blow Proctor tests closely estimated the density increases for the 7.5 and 15 cm depths, respectively, for uphill skidding.

Smith, R.A. 1988. Environmental impact of ground harvesting systems on steep slopes in the Vernon Forest District. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 13-27.

The impact of conventional ground harvesting systems on steep slopes was examined. Disturbance levels ranged from 17 to 61%. Excessive excavation on many sites often led to slope failure and surface erosion. Regeneration on the compacted surfaces was usually growing poorly or was nonexistent. Many of the skidroads and landings were intercepting surface and/or ground water flow, resulting in surface erosion and channelling of water. Guidelines for skidroad and landings were drafted to minimize site degradation through the modification of harvesting systems or the use of alternative yarding equipment.

Smith, R.B. and E.F. Wass. 1980. Tree growth on skidroads on steep slopes logged after wildfires in central and southeastern British Columbia. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-R-6. 28 p.

The growth of Douglas-fir, western larch, lodgepole pine and Engelmann spruce on contour skidroads was measured 16-18 years after salvage logging of steep wildfire-burnt areas. This growth, when compared to that of trees growing on adjacent (above and below) non-roaded surfaces, was found to vary with species, soil, and climate. A system was thus devised to rate sites on their sensitivity to disturbance according to tree growth on the disturbed surfaces. Tree growth was reduced most on calcareous or strongly acid, coarse-textured or shallow soils in wet climates. The least sensitive sites were those with slightly acid, non-calcareous, medium to moderately coarse-textured soils in dry climates. The study areas were located in the IDF IDF/ESSF transition, ICH, ICH/ESSF transition, and ESSF biogeoclimatic zones.

Warrington, G.E. 1978. Estimating soil erosion for forest land management planning: a procedure. *In* Forest soils and land use. C.T. Youngberg (editor). Proc. 5th N. Am. For. Soils Conf. Col. State Univ., Dep. For. Wood Sci., Fort Collins, CO. pp. 174-197.

A previously developed surface soil erosion model was prepared for use in the land management planning process. Procedures are presented for estimating model coefficients and incorporating the results into a forest land management planning process. The erosional consequences from different management alternatives in the Pacific Northwest are discussed.

7 HANDBOOKS AND GUIDELINES

7.1 Summary

The research results available in the literature make it increasingly clear that excessive soil disturbance can be a significant problem over a broad range of B.C. soil conditions, tree species, and equipment and treatment types, and also that some practical and effective management approaches are available for minimizing problems (Froehlich and McNabb 1984). However, for land managers, field staff, and equipment operators, soil degradation-site productivity issues often remain complex from both a technical and administrative viewpoint. Additionally, the standard research communications are easily overlooked by operations personnel or, perhaps worse, misinterpreted or misapplied.

What we have lacked in B.C. over the past several years has been an active extension program for effective distribution of the research results and interpretations to individuals who can apply them to their land management and forest operations. The most substantial part of the extension network available to operations staff has been the handbooks and guidelines produced either as specific publications or as parts of other publications.

Handbooks and guidelines should provide those people responsible for making harvesting and forest renewal prescriptions a choice of strategies for forest management without causing excessive site degradation and corresponding losses in long-term forest productivity. For prescription development, forest managers should have access to an objective and efficient process for assessing site conditions and the relative sensitivity of a site to degradation; and a selection of alternative, practical solutions for altering forest management practices to suit the varying degrees of sensitivity observed. Obviously, to be effective, handbooks and guidelines should stress the importance of the planning process: the biological importance, the management importance, and the economic importance. Proper implementation of the guidelines available saves time, money and the resource, all admirable and responsible goals for forest managers.

The handbooks and guidelines reviewed in Section 7.2 concentrate on three aspects of harvesting and forest renewal: pre-harvest prescription development, prescription implementation and assessment, and mitigative or rehabilitation measures if soil degradation occurs. Responsible pre-harvest prescription development is impossible without an evaluation of site conditions and regeneration potential, an identification of sensitive areas, an awareness of management options available to prevent soil degradation and productivity losses, and integrated management objectives. From a harvesting point of view, there is evidence that the use of planned, designated skid trails leads to substantially lower site compaction levels and lower site productivity losses, with no increases in logging costs or losses in machine productivity. Selective road location, proper road construction, and responsive road maintenance and protection are all considered to be integral parts of responsible forest land management. Minimization of soil disturbance levels and of changes to normal drainage patterns in a setting will help protect the soil resource, the forest resource, and off-site resources, and will help provide economic opportunities and employment in the future.

For site preparation considerations, guidelines are available to aid managers in evaluating site conditions, selecting treatment options, implementing treatments, monitoring treatment progress and success, and assessing post-treatment site conditions. By no means are guidelines available for all site types or all equipment types, but at least possible problem areas are highlighted and can help managers with their intuitive planning.

The use of well-prepared management plans does not imply that no soil degradation or site productivity losses will occur. Some degradation is unavoidable, and at times the best laid plans fail. For whatever reason implementation failures may occur, there are procedures/measures/tools which can be used to ameliorate the degradation and control further site deterioration. There are guidelines for the use of these procedures/ measures/tools, but it must be emphasized that reclamation or rehabilitation is more costly than planning and prevention and that excessive soil degradation can lead to rotation-length losses of commercial crop.

7.2 Annotated Literature

Adams, P.A. and H.A. Froehlich. 1981. Compaction of forest soils. USDA For. Serv., Pac. NW Extens. Publ. PNW-217. 13 p.

Logging and other mechanized activities often lead to soil compaction, which can reduce seedling and residual tree growth and promote surface erosion. The extent of these impacts is largely a function of the initial soil characteristics, the amount and type of forces applied, and the resulting area and depth of compacted soil. The land manager must balance the expected effects and related costs of compaction with economical techniques for minimizing the problem and improving the situation. Among the most promising methods for accomplishing this are the use of designated skid trail systems and soil tillage.

Adams, P.A., J.J. Garland, and H.A. Froehlich. 1985. Research and extension programs lead to effective management of forest soil compaction in the Pacific Northwest. *In* Foresters' future: leaders or followers. Proc. 1985 SAF Nat. Conv., Fort Collins, CO. pp. 121-124.

Initial research into soil compaction problems and solution focused on documenting the occurrence and impacts of compaction. More recent studies have examined potential management alternatives and their operational efficiency and costs. Extension activities at Oregon State University have closely followed research developments, and have included workshops, publications, and audio-visual productions which have reached many foresters and operators.

Anonymous. 1985. A guide to prescribed broadcast burning in the Vancouver Forest Region. B.C. Min. For., Vancouver, B.C. and MacMillan Bloedel Limited, Nanaimo, B.C. 110 p.

This guide is designed to complement the existing guides for tree species selection, prescribed fire prediction, and planning for burning; and to help forest land managers attain fuel reduction and vegetation management objectives by improving their technical expertise in conducting prescribed burns. This guide is written with the assumption that the reader has the ability to assess site quality by using climatic (biogeo-climatic units) and edaphic (soil moisture and nutrient regime) factors. It also assumes that the users understand the Canadian Forest Fire Danger Rating System and the significance of its various components.

Anonymous. 1987. Better harvesting practices for protecting forest soil. B.C. Min. For. Lands, Silv. Br., Victoria, B.C. 29 p.

This booklet offers guidelines for soil protection during forest harvesting and road building. Forest soil protection is equated with maintaining forest productivity, maintaining the quality of the environment, and providing jobs and forests for the future. Two simple guidelines are given:

1. minimize or reduce the area of soil disturbance; and
2. minimize changes to the normal drainage pattern of the land. These guidelines are then applied to road location, construction and maintenance; protection of roads after logging; and tractor and cable logging.

Anonymous. 1987. Ground skidding guidelines with emphasis on minimizing site disturbance. Engineer. Br. and Silv. Br., B.C. Min. For. Lands, Victoria, B.C. 58 p.

This handbook is intended to reach field staff who have a day-to-day influence on the occurrence and extent of soil disturbance — that is, those personnel engaged in the planning, implementing and controlling of ground-skidding operations. It pertains to well-drained, low level coastal areas and those interior regions of B.C.

where ground-skidding methods are feasible. Most of the principles and guidelines stated in the handbook are also applicable to the northern and northeastern areas of the province where prolonged severe winter conditions may require some modification of the methods and procedures presented in the handbook. This handbook does not present rigid directives to the resource manager, but rather a suggested set of guidelines that recognize the difficulties caused by the great variety of conditions which might affect the application of harvesting principles. The handbook has two major sections:

1. soil disturbance in ground skidding, which describes problems associated with this harvesting method; and
2. planning, layout and construction guidelines, which describes ways to reduce soil disturbance caused by construction of haulroads, skidroads and landings.

Boyer, D. 1979. Guidelines for soil resource protection and restoration for timber harvest and post-harvest activities. USDA, For. Serv., Pac. NW Region Watershed Manage. Unpubl. Rep. 42 p. and 14 appendices.

This report provides guidelines for soil resource protection by the prescription and monitoring of harvest and post-harvest activities. It also discusses the types of soil water alterations that potentially cause a significant reduction in the productive base for forage and fiber, and it describes the principal activities which potentially damage the soil resource. It also includes suggested methods of restoration.

Breadon, R.E. 1983. Timber development planning for the British Columbia interior: the total chance concept. FERIC, Vancouver, B.C. Handb. No. 4. 73 p.

This handbook describes the appropriate level of total-chance planning for a relatively steep interior drainage requiring coordination of road development with harvesting systems. ‘‘Total chance’’ refers to early planning over an entire development area for the best overall realization of all objectives identified by broader planning. The handbook describes the kinds of information needed for planning a development area, describes the road construction and harvesting system choices available and their capabilities, and works through an example of the development area planning process. Planning success will depend on the availability of reliable maps and information for the drainage; well-defined operating objectives; group reconnaissance trips; careful system choices; thorough paper-planning and field checking; thoughtful review of all implications of the plan; a readiness to change the plan for good reasons; good communications between the planners, the doers and the government regulators; and the extent to which such factors as weather and markets cooperate during the implementation of the plan.

Carr, W.W. 1980. Handbook for forest roadside erosion control in B.C. B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 4. 43 pp.

Recommended procedures for controlling the erosion from roadsides are presented.

Carr, W.W., W.R. Mitchell and W.J. Watt. 1988. Basic soil interpretations for pre-harvest silviculture planning - surface soil erosion, soil compaction. Terrasol, Vancouver, B.C. Unpubl. Rep. 34 p.

This report provides guidelines for assessing surface soil erosion and soil compaction hazards. The soil erosion and compaction hazard indices presented for inclusion in the pre-harvest silvicultural planning process are modifications of previous systems. The modifications reflect advances in forest soil research which will improve their predictive capability. Neither index requires the collection of field data other than that normally gathered on FS 711 or in the biogeoclimatic and site mapping procedures.

Cleary, B.D. and B.R. Kelpsas. 1981. Five steps to successful regeneration planning. Oreg. State Univ., For. Res. Lab., Corvallis, OR. Special Publ. 1. 31 p.

Planning for successful reforestation by planting is difficult because many variables must be integrated to produce a carefully designed and economical plan. Without a systematic approach, essential elements are often neglected or overlooked. This handbook presents a method in which planning information is organized step-by-step and then used as the basis for choosing among possible alternatives. In the first four steps, site information is compiled, harvest systems are analyzed, seedling environment is assessed, and site preparation alternatives are evaluated. In the fifth and final step — the prescription formulation — the harvest system is selected, the site preparation method, stock type, and seedling handling and planting practices are determined, and operations for plantation maintenance are identified. A sample prescription illustrates the application of this plan to a specific site.

Coates, D. and S. Haeussler. 1984. A guide to the use of mechanical site preparation equipment in North Central British Columbia. B.C. Min. For., Victoria, B.C. 54 p.

This field guide reviews the mechanical site preparation techniques suggested for the Prince Rupert, Prince George, and Cariboo Forest Regions. It describes approximately 15 types of mechanical site preparation currently in use, along with the user's assessment, prices, and productivity. The guide also outlines a reference table for determining the ability of each type of equipment to perform under different site conditions, and gives mechanical site preparation interpretations for ecosystem association groups in the SBS, ICH, ESSF and BWBS biogeoclimatic zones.

Coates, D. and S. Haeussler. 1985. A preliminary guide to the response of major species of competing vegetation to silvicultural treatments. B.C. Min. For., Victoria, B.C. Land Manage. Handb. No. 9.

The ecosystem classification system used by the B.C. Ministry of Forests provides a framework for describing the vegetation complexes that develop following forest harvesting and the various environments in which they grow. The process of characterizing seral plant communities has begun, but it will be some time until forest ecologists and silviculturists will be able to make informed predictions about the development of vegetation on different ecosystems following harvesting. In the meantime, it is important to identify and understand the individual species which make up the vegetation complexes that compete with crop trees. Foresters have tended to consider all shrub and herbaceous vegetation as just "brush." This handbook helps make foresters more aware of some of the differences that exist among these various species of brush and their responses to silvicultural treatments.

Comeau, P.G., M.A. Comeau, and G.F. Utzig. 1982. A guide to plant indicators of moisture for south-eastern British Columbia, with engineering interpretations. B.C. Min. For., Nelson, B.C. Land Manage. Handb. No. 5. 119 p.

This guide was prepared to assist field personnel in the use of plant indicators to recognize and evaluate soil moisture conditions. The plant species included are reliable indicators of the presence of seasonal or permanent water near the soil surface for the indicated biogeoclimatic subzones. Hazard prediction keys (compaction, erosion, mass wasting, windthrow, frost heave and culvert requirement information) are presented.

Forest Engineering Research Institute of Canada. 1976. Handbook for ground skidding and road building in the Kootenay area of British Columbia. Vancouver B.C. 41 p.

This is a handbook for skidder operators, bulldozer operators, fallers, and other related personnel. It discusses ways of improving ground-skidding and road-building practices so that trees can be cut, skidded, and hauled efficiently, with a minimum of soil disturbance.

Froehlich, H.A., D.E. Aulerich, and R. Curtis. 1981. Designing skid trail systems to reduce soil impacts from tractive logging machines. Oreg. State Univ., For. Res. Lab., Corvallis, OR. Res. Paper 44. 15 p.

Logging on skid trails restricted to 10% or less of the harvested stand can reduce the area of compacted soil by at least two-thirds. In a comparative study, productivity of Douglas-fir logs per hour was just as great in an area with designated trails as in an adjacent area logged conventionally. Logging on designated trails required more winching time, but this increase was offset by a reduction in skidding time. Furthermore, there was less damage to residual trees on the area with designated trails. The use of such trails is economical and efficient if trees are felled to the lead of the trail.

Garland, J.J. 1983. Designated skid trails to minimize soil compaction. *In* The woodland workbook - logging. Oregon State Univ., Extension Serv., Corvallis, OR. Extens. Circ. 1110.

Soil compaction and disturbance problems can be reduced by restricting the amount of ground area covered by skid trails during harvesting operations. A reasonable goal is to confine the area covered by skid trails to <15% of the area, including landings, but excluding haulroads. Restricting the area in skid trails requires advance planning, clearly flagging trails before logging, and pulling the winch line from the tractor (rubber-tired skidder, crawler tractor, or low ground pressure vehicle) to logs or trees ''felled to lead'' to the skid trail.

In a study comparing conventional skidding, where the machine operator selects the skid trail, to the use of planned and designated skid trails, research showed the average winch line pulled to be about 9 m for conventional skidding versus about 10 m for designated skid trails spaced 100 ft apart. Despite little difference in winching, there was a large difference in the amount of area covered by skid trails. Planned and designated skid trails can be considered as a permanent part of the transportation system and can be used for later entries into timber stands for future management and harvest activities. Research and field experience indicates that this harvest system may be only slightly more expensive, and sometimes even less expensive, than conventional practices.

Hammond, H.L. 1982. Ground skidding handbook for the Nelson Forest Region. B.C. Ministry of Forests, Nelson, B.C. Unpubl. Rep. 47 p.

This handbook is primarily a field guide for managers and operators to use at the block and harvest plan level. Included are a method for describing site and harvest characteristics, guidelines governing improved ground-skidding operations, and planning and layout procedures. Operational expectations and models are also provided so that operators and managers may anticipate design problems and evaluate the success they have had in combining efficient ground skidding with minimal site degradation.

Hedin, I.B. 1978. Timber and slope characteristics influencing future harvesting in British Columbia. FERIC Tech. Report TR-21.

This report correlates forest inventory information with topographic maps. Five slope classes and six diameter classes were used, corresponding to the mobility and felling capabilities of different harvesting systems. The trees per acre, height range, and total-stem volume per acre were calculated, with the use of a computer program, from the inventory sample-plot data.

Howes, D.E. and M. Sondheim. 1988. Quantitative definitions of stability classes as related to post-logging clearcut landslide occurrence. Part II. *In* Degradation of forested land: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 167-184.

Slope stability following clearcutting is examined in the Norrish-Cascade watershed, using a terrain evaluation method developed over the past 5 years. The polygons of a surficial geology map are placed into terrain classes, which are defined by factors identified from a detailed landslide survey. Each of these classes is assigned to one of four stability classes based on a clearcut-related, slides-per-clearcut hectare criterion. Other terrain class statistics include the number of natural slides per hectare, the probabilities of both natural- and clearcut-induced slope failures occurring in a polygon, the ratio of these probabilities, and the ratio of the clearcut and natural rates on a per-hectare basis.

Howes S. and D. Hughes. 1981. Forest soil horizons. USDA For. Serv., Pac. NW Region, Portland, OR. Unpubl. Rep. No. 7.

A presentation is made of available models and techniques for computing on-site erosion losses and mass movement, sediment delivery indices, and erosion hazard ratings. Descriptions are included of predictive equations used, data requirements, procedures for computer or calculator execution, and appropriate references.

Lewis, T. 1988. Guidelines for timber harvesting prescriptions for interior sites of various degradation sensitivities. Timber Harvesting Methods Committee, B.C. Min. For. Lands, Victoria, B.C. Unpubl. Rep. 65 p.

This report proposes two approaches to objectively assessing the risk of degradation during harvesting — a hazard approach and a site factor approach — using the premise that to avoid unnecessary degradation requires a sound assessment of risk prior to planning an operation. Such an assessment fits very well into the now established pre-harvest assessment process, involving only marginal increases in data requirements from that already collected. Suggestions and recommendations for modifications to standard logging practices, on a phase by phase basis, are included to aid the formulation of prescriptions that are tailored to suit differing levels of degradation sensitivity. Negative impacts can be minimized if prescriptions are modified to fit the landscape (which can be interpreted as a mosaic of treatment units each having an intrinsic sensitivity to timber harvesting). A range of site rehabilitation options is presented as well, but the report stresses that avoidance of degradation is usually both simpler and less costly than rehabilitation, particularly since the long-term effectiveness of some rehabilitation techniques is still uncertain.

Lysne, D. 1983. Using designated skid trails. B.C. Min. For. Unpubl. Rep. F.S. 189 (1) INF 83/5.

This a guide to understanding the factors controlling the use of designated skid trails. These factors include the amount of winch line typically spooled by ground-based logging vehicles, skid trail patterns, skid trail spacing in relation to falling patterns, log lengths and feet of winch line pulled, effort required to pull winch lines, pull required to skid logs, and land management practices.

McLeod, A.J. 1983. Technical paper describing problems and strategies associated with harvesting sensitive slopes in the Prince George Region. B.C. Min. For., Prince George, B.C. Unpubl. Rep. 34 p.

This report updates the strategies for harvesting steep-slope areas in the Prince George Forest Region. The recommendations in this report are meant to be used as a guide pinpointing concerns and giving the user some ideas for selecting appropriate harvesting systems. Detailed operational guidelines are being developed that will enable users to develop and adopt site-specific strategies in the Prince George Forest Region.

McMinn R.G. 1984a. Guidelines for mechanical site preparation. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Unpubl. Rep. 17 p.

This report uses the broad stratification — hot/dry climates and cool/moist climates — to demonstrate some of the essential considerations governing the use of mechanical site preparation equipment. For site preparation to be effective, managers must know which factors are detrimental to seedling performance and what remedial action will be successful. While this seems obvious, site preparation experience is not without examples of ineffectiveness because the problem was not properly understood or the remedial action was inadequate.

Packer, P. E. 1967. Criteria for designing and locating logging roads to control sediment. For. Sci. 13 (1): 2 -18.

The criteria are presented for the design, location and construction of logging roads in the northern Rocky Mountains to control erosion and sediment. The study shows that the spacings of logging road cross drains and widths of protected strips are affected significantly by several watershed and road characteristics, information which is usually readily available to forest managers.

Still, G.W. and D. Macdonald. 1987. Maintaining productive forest soils...our future depends on it. B.C. Min. For. Lands, Nelson, B.C. and Victoria, B.C. Inf. brochure. 6 p.

harvesting and site preparation. Recommendations are made for improving harvesting and site preparation practices and for implementing rehabilitation measures in B.C., all oriented to the maintenance of soil productivity and the provision of a future forest resource.

Trowbridge, R., B. Hawkes, A. Macadam, and J. Parminter. 1986. Field handbook for prescribed fire assessments in British Columbia: logging slash fuels. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Handb. No. 11. 63 p.

This handbook contains standard methods of prescribed fire research assessments for logging slash fuels in B.C., and describes the procedures for making pre-burn assessments, observations during the fire, and post-burn assessments. All procedures included are oriented toward documenting and evaluating broadcast prescribed fire. The handbook is designed solely for voluntary operational assessments. It is intended to document the prescribed fire treatment and to assess the success or failure of specific fire prescriptions for particular sites and site types. The assessments are plot-based. Sites must be stratified according to topography and ecosystem distribution, and fuel type and loading. A minimum of two plots per stratum is required for an assessment, and one or more assessments may be done in any treatment site. It is anticipated that these assessments, complemented by research trials and experiments, will lead to the refinement of fire prescriptions, and fire behaviour and impact (fuel and site) models in B.C.

CHAPTER II: COSTS AND PRODUCTIVITY OF INTERIOR BRITISH COLUMBIA FOREST HARVESTING EQUIPMENT AND OPERATIONS

1 SUMMARY

This annotated bibliography has reviewed the literature which documents productivities and costs of timber harvesting equipment and systems operating in circumstances comparable to those found in interior British Columbia. The bibliography's scope covered only primary harvesting activities (falling, skidding or yarding, limbing and bucking, and loading). Secondary transportation (i.e., hauling) and processing were not included.

The volume of research which is directly useful to this survey is small because most of the literature from outside B.C. describes operating situations not representative of the B.C. interior. Despite the wide spectrum of systems and equipment currently used, related productivity and cost information is incomplete. Furthermore, some of the available information is dated.

The major findings of this review are:

1. Most of the relevant literature focuses on entire harvesting systems rather than logging phases, although in a number of studies the role of a particular machine type is emphasized. Cable systems and alternative ground-skidding systems (e.g., small crawler tractors or FMC's) received considerably more attention than conventional harvesting systems. In general, conventional ground-skidding methods appear to be more cost-effective than alternative ground-skidding systems or cable systems. Based on results from several studies, production costs of small crawler tractors and FMC's average from 10 to 20% more than conventional crawler tractors or rubber-tired skidders (Table 1). Cable-yarding costs range between 65 and 160% higher than conventional costs (Table 1).

   The latest B.C. Interior harvesting study published by FERIC (Krag and Webb 1987) indicated a cost on-truck of \$11.34/m^3 for a conventional system of three rubber-tired skidders and a medium-sized crawler tractor (Table 1). The cost of a system of four to five small crawler tractors and one trail-building tractor was 17% greater at \$13.25/m^3, while a cable system (Rosedale Ecologger) cost \$18.60/m^3, or 64% more than the conventional system (Table 1).

   Higher capital cost is a major component of increased production costs for cable yarders and FMC's, even though they may out-produce conventional harvesting equipment on a per-machine basis. Other organizational factors, such as the need to dedicate a loader to a cable yarder to keep landings clear, also contribute to higher costs.

2. Some logging phases, such as mechanical felling, have been studied intensively, while other phases have received little or no attention. Phase costs are usually presented in logging systems studies, but comparisons are often difficult. Some, such as hand-falling, are often based on estimated production rather than measured production, while other phases are more carefully monitored. Comparisons of phase productivities and costs between different logging systems are usually complicated further by differences in operating methods.

3. Most logging systems studies describe only a narrow range of potential operating chances. For example, many of the studies reported here are concerned with steep-slope logging operations. Thus, more information is available for cable systems and alternative ground-skidding systems than for conventional operations on gentle terrain. The effects of some factors — such as timber size and quality, terrain, climate, crew experience, and operating technique — on productivity and cost are not well documented. The studies summarized in this report show that productivity can vary considerably for a given logging system. In the reports included in this survey, machine productivity (m^3/Productive Machine Hour) ranges from 22.4 to 32.0 for conventional grapple-skidding equipment, 5.2 to 8.1 for small crawler tractors, 8.0 to 23.6 for FMC's, and 4.4 (Mini-Alp) to 38.1 (Skagit GT3) for cable yarders (Table 1). This indicates that external factors are important determinants of productivity and cost.

TABLE 1. Summary of the costs, productivities, and site disturbances reported in the harvesting studies carried out in the interior of British Columbia

Investigator and date	Region	Machine	$/m³	m³PMH	Comments	S.D.%	Comments
A) Cable systems							
Cottell *et al.* 1976	East side Purcell Mtns.	Rosedale Ecologger	10.24	15.8	All costs include felling, limbing, bucking, yarding (and/or skidding), and loading unless otherwise noted.	s = summer w = winter	
Cottell *et al.* 1976	West side Purcell Mtns.	Madill 70 ft.	11.0	24.1			
Cottell *et al.* 1976	East side Monashee Mtns.	Madill 70 ft.	11.28	16.1			
Cottell *et al.* 1976	West Side Selkirk Mtns.	Madill 071	10.32	15.4			
Cottell *et al.* 1976	Grande Prairie Alberta	Madill 071	9.60	18.3			
Cottell *et al.* 1976	East side Monashee Mtns.	Washington 078 Grapple Yarder	8.08	21.2	Cost of mobile backspar also included.		
Cottell *et al.* 1976	Cariboo	Skagit GT3 Grapple Yarder	8.86	32.4	Cost of mobile backspar also included.		
Cottell *et al.* 1976	Okanagan	Koehring Bantam	0/04	11/7			
Krag and Webb 1987	B.C. Central Interior	Rosedale Ecologger	18.60	13.3 per system hour		10 (s) 7.6 (w)	Total detrimental soil disturbance
McDonald 1979	Southeastern B.C.	Critical site Yarder	15.24	10.5			
McDonald 1981	B.C. Central Interior	Finning SY235	13.15	34.9			
McDonald 1981	B.C. Central Interior	Skagit GT3	12.18	32.6			
McMorland 1978	B.C. Central Interior	Skagit GT3	7.96	38.1	(1976 $)		
McMorland 1978	Southeastern B.C.	Igland-Jones (mini-Alp)	17.59	4.4	(1976 $)		
B) Ground skidding (conventional)							
Hedin 1980	Okanagan	Grappel Skidders (summer)	14.18/ C.P.Y. 12.17/ Conven.	24.7/ C.P.Y. 22.4/ Conven.	Cost also includes landing construction and hauling.		
Hedin 1980	Okanagan	Grappel Skidders (winter)	10.54/ C.P.Y. 9.77/ Conven.	33.2/ C.P.Y. 32.0/ Conven.	Cost also includes landing construction and hauling.		
Krag and Webb 1987	B.C. Central Interior	Wheeled Line Skidders	11.34	32.9 per system hour	Cost of truck including trailbuilding.	24.4 (s)	Total detrimental soil disturbance

TABLE 1. Continued

Investigator and date	Region	Machine	$/m³	m³PMH	Comments	S.D.%	Comments
C) Ground skidding (alternative)							
Krag and Webb 1987	B.C. Central Interior	Small Crawler-Tractor System	13.25	34.2 per system hour	Cost on truck including trailbuilding.	18.0 (s) 12.6 (w)	Total detrimental soil disturbances
McMorland 1977	Okanagan	Volvo Clam Bunk Skidder	1.76 to 5.05	20.8/ Clearcut 22.8 R/W	Costs for skidding only.		
McMorland 1980	Southeastern B.C.	Small Crawler-Tractor System	8.19	8.1	Cost of decked wood on a landing.	29.3	Percent of site disturbed (all depth classes). 44.5% for large tractors.
McMorland 1985	Southeastern B.C.	FMC FT-180	8.0/ Clearcut 17.1 R/W				
McMorland 1985	Southeastern B.C.	JD550	5.2 Clearcut 17.1 R/W				
Powell 1978	Southeastern B.C.	FMC 200BG	4.96	15.0	Skidding cost only.		
	Southeastern B.C.	FMC 200CA	2.71 to 3.66	18.6 to 23.6			

2 ANNOTATED LITERATURE

This annotated bibliography identifies available literature and sources of information on productivities and costs of timber harvesting equipment, phases, and systems relevant to Interior B.C. conditions.

Production costs presented in this report are the actual costs for the year in which a particular study was done. Costs have not been standardized to 1989 Canadian dollars, so direct comparison of costs between studies is not possible.

Publications included in this bibliography satisfy the following criteria:

1. They have been published within the last 15 years;
2. They describe logging operations and situations which represent, or are closely similar to, current Interior B.C. harvesting methods, timber, terrain, and climate; and
3. They quantify and substantiate harvesting costs and production.

The following publications have resulted from studies on timber harvesting equipment and systems in the interior of B.C. In addition to the reports listed, FERIC has reports available on the production and performance of delimbing and processing equipment in the Interior. Extensive work has also been done on factors influencing butt damage during felling and the levels of butt damage associated with different felling heads.

Anderson, C.H. 1977. Methods of reducing capital cost of logging equipment suited for harvesting Interior timber types in British Columbia. Report prepared for the Forest Engineering Research Institute of Canada. 93 p.

The engineering aspects of introducing cable harvesting systems to the B.C. Interior are examined. The parameters that determine a machine's minimum and maximum operational specifications and characteristics are determined by a group of factors which the author summarized under the headings of timber type, terrain limitations, and non-physical factors (labour, training, etc.). The cost of adapting used cranes is compared to that of new machinery.

B.C. Ministry of Forests and Lands. 1986. Interior end-product appraisal manual. Victoria, B.C.

This manual contains tree-to-truck cost estimates for the B.C. Interior based on an industry contract rate survey. Four main logging method groupings are presented:

1. crawler-tractor skidding;
2. soft-tracked skidding;
3. other skidding: all remaining ground-skidding systems including feller bunchers, tree shears, hand falling, and/or falling and bucking with rubber-tired grapple or line skidders; and
4. cable yarding.

This contract rate survey method of estimating Interior logging costs has been used since 1985. In 1984 and previous years, production monitoring studies were used to determine the average production per hour of harvesting equipment operating under certain conditions. Individual contracts and production studies are classified as confidential by the Ministry of Forests. Detailed time studies of harvesting operations have not been performed by the Ministry of Forests since approximately 1977.

Bradshaw, G. 1979. Preplanned skid trails and winching versus conventional harvesting on a partial cut. Oreg. State Univ., For. Res. Lab., Corvallis, OR. Res. Note No. 62. 4 p.

Production rates, skidding costs, and soil disturbance are compared for two partial-cut units: one with pre-planned skid trails and winching, and one conventional unit. The unit with pre-planned skid trails and winching had 11% less production and a 29% higher skid cost than the conventionally harvested unit. However, only 4% of its area was in skid trails, compared to 22% for the conventionally harvested unit.

Breadon, R.E. 1983. Timber development planning for the British Columbia interior: the total-chance concept. FERIC, Vancouver, B.C. Handb. No. 4. 73 p.

This handbook presents the ''total-chance'' method of timber development planning for the B.C. Interior. The ''total-chance'' concept was described as ''early planning over an entire development area for the best overall realization of all objectives identified by broader planning.'' The kinds of information needed for planning are described. Typical production levels and operating capabilities for harvesting systems found in the Interior are also described. This handbook also contains a detailed example of ''total-chance'' planning for a relatively steep Interior drainage.

Cottell, P.L., B.A. McMorland, and G.V. Wellburn. 1976. Evaluation of cable logging systems in Interior B.C. and Alberta. FERIC, Vancouver, B.C. Tech. Rep. No. TR-8. 41 p.

This report presents the results of case studies of cable logging operations in Interior B.C. and Alberta over the period of June 1974 to March 1976. The following machines were examined: Rosedale Ecologger; Madill 071 Skidder Tower (Mini Spar) (two); Koehring Bantam (loader converted for yarding); older model 70-foot Madill tower (two); Washington 078 grapple yarder; and Skagit GT3 grapple yarder. Summarized individually, each case study includes a general description of the logging system; basic machine specifications and forest site characteristics; production study results from short-term, intensive time studies (time distribution, log sizes, turn volumes); and longer-term performance (production, availability and machine utilization) from the shift reports.

Productivities (cubic meter per productive machine hour [or PMH]), yarding costs only, and average piece sized for each machine are as follows:

	m^3/PMH	\$/m^3	m^3/piece
Skagit GT3	32.4	4.88	0.84
Washington 078	21.2	5.55	0.87
Rosedale Ecologger	15.8	5.57	0.62
Koehring Bantam	11.7	6.77	0.36
70-ft Madill Spar #1	24.1	6.73	1.06
70-ft Madill Spar #2	16.1	6.97	0.78
Madill 071 Mini-Spar #1	15.4	7.43	0.81
Madill 071 Mini-Spar #2	18.3	5.74	0.84

Including falling, limbing and bucking, swinging, and loading, the cost of logs loaded on the truck ranged from \$8.08/m^3 (for the Washington 078) to \$11.28/m^3 (for the 70-ft Madill Spar #2), compared to \$4.00-\$6.00/m^3 for conventional ground-skidding systems.

Froehlich, H.A., D.E. Aulerich, and R. Curtis. 1981. Designing skid trail systems to reduce soil impacts from tractive logging machines. Oreg. State Univ., For. Res. Lab., Corvallis, OR. Res. Paper 44.15 p.

Logging on skid trails restricted to 10% or less of the harvested stand can reduce the area of compacted soil by at least two-thirds. A comparative study in a thinning operation resulted in similar production (20 trees per hour vs. 19) for both the area with designated trails and the conventional area. The authors concluded that the results of this and previous studies indicate that a policy of installing designated skid trails for thinning and harvesting will minimize soil compaction and thereby enhance forest productivity.

Gairns, G.H. 1987. Logging contract survey. Industrial For. Serv. Ltd., Prince George, B.C. (Compiled annually.)

This report contains logging contract rate survey questionnaires from companies throughout the B.C. Interior and Alberta. The collected data is statistically analyzed to determine the main factors influencing costs. Equations are derived for both logging and haul cost estimation.

Gardner, R.B. 1980. Skyline logging productivity under alternative harvesting prescriptions and levels of utilization in larch-fir stands. USDA For. Serv., Intermount. For. Range Exp. Sta., Ogden, UT. Resource Paper INT-247. 35 p.

This paper presents the production results of a study in which four levels of utilization — from conventional sawlog to almost total fibre recovery — were compared using running skyline and live skyline yarding harvesting systems. All four levels of utilization were applied under each of three silvicultural prescriptions: shelterwood, group selection, and clearcut harvesting.

Average production, under conventional sawlog utilization (14-cm top) and with an average piece size of 0.42 m^3 was 28 m^3/PMH for a Skagit GT3. The machine was rigged as a running skyline and was yarding uphill. A Link Belt 78 Log Mover, rigged as a skyline and yarding uphill, averaged 26.4 m^3/PMH with an average piece size of 0.37 m^3. With close log utilization (8-cm top) production decreased to 17.6 m^3/PMH for the GT3 and 14.2 m^3/PMH for the live skyline system. No cost analysis was reported.

Gardner, R.B. 1982. Estimating production rates and operating costs of timber harvesting equipment in the Northern Rockies. USDA For. Serv., Intermount. For. Range Exp. Sta., Ogden, UT. Gen. Tech. Rep. INT-118. 29 p.

Summarizes studies of ground, cable, and aerial logging systems in the Northern Rockies over a 15-year period. Provides nomographs and tables for calculating productivity and expected costs.

Hedin, I.B. 1980. Comparison of two logging systems in Interior British Columbia: central processing yard vs. conventional. FERIC, Vancouver, B.C. Tech. Rep. No. TR-45. 53 p.

This report compares the costs and productivities of a conventional Interior harvesting system to that of the Central Processing Yard (CPY) system. The company involved harvested one-half of a timber block conventionally and the other half through a central processing yard. The study took place in January 1979 and was repeated in June under summer conditions. Both operations used feller bunchers and grapple-skidders. The conventional system used only highway trucks, while the CPY system also used off-highway trucks for hauling. Utilization of equipment and manpower was better in the CPY system but total hours and cost per cubic meter increased.

The total cost of the CPY system was 7% higher in the winter ($10.54/m^3 vs. $9.77/m^3) and 14% higher in the summer ($14.18/m^3 vs. $12.17/m^3). The CPY system had lower terminal times for skidding, resulting in higher production. Skidding productivity for the CPY system was 24.7 m^3/PMH ($2.16/m^3) in the summer and 33.2 m^3/PMH ($1.61 m^3) in the winter. The conventional system produced 22.4 m^3/PMH ($2.39/m^3) in the summer and 32.0 m^3/PMH ($1.67/m^3) in the winter. The average piece size was 0.36 m^3. The decrease in production over the summer period reflects the more difficult terrain encountered. Felling productivity and costs were not studied. Company averages of $1.77/m^3 for the easier winter terrain and $1.94/m^3 for the steeper summer terrain were used for felling costs. Skidding production increased 3.8% in the winter and 10% in the summer with the CPY system.

The costs involved with each phase of the operation are presented in such a way that the per cubic meter costs for a specific operation can be calculated. The study did not show any distinct advantage in either system, indicating that the choice of central processing must be made after considering the specific timber conditions, logging chance, haul route, and mill requirements.

Kellogg, L.D. 1981. Machines and techniques for skyline yarding of smallwood. Oreg. State Univ., For. Res. Lab., Corvallis, OR. Res. Bull. 36. 15 p.

Research on skyline machines and techniques currently available for yarding smallwood is reviewed. Three categories of machines are discussed: used yarders (with a low initial cost) adaptable to smallwood; new and versatile yarders (with a high initial cost) manufactured in the U.S.; and new, foreign-built yarders (with a low initial cost) specifically developed for smallwood. Used, inexpensive yarders can be a viable option for yarding smallwood, but carriage selection and timber size are important considerations. Pre-bunching small logs with a separate, low cost system can increase yarding production and lower harvesting costs incurred with expensive new yarders. Proper determination of crew size and equipment balance can produce more cost- effective use of new, low-cost yarders.

Krag, R.K. and S.R. Webb. 1987. Cariboo Lake logging trials: a study of three harvesting systems on steep slopes in the Central Interior of British Columbia. FERIC, Vancouver, B.C. Tech. Rep. No. TR-76. 48 p.

A field trial was conducted to determine whether small crawler tractors could log steep slopes in the Central Interior of B.C. and satisfy economic and environmental constraints. Log production and soil disturbance were measured for small crawler-tractor and cable-yarding (Rosedale Ecologger) systems from June 1984 to March 1985. For additional comparison, a rubber-tired line skidder operation was also monitored for a 6-week period in the summer of 1984. The small crawler-tractor system consisted of four or five skidding tractors, each operating on separate landings, one trail-building tractor, and one front-end loader. The cable-yarding system consisted of one 18-m tower and one front-end loader. The conventional system consisted of three rubber-tired skidders, one medium-sized crawler tractor which built trails as well as skidded logs, and one front-end loader.

In the summer, the small crawler tractors, cable yarders, and rubber-tired skidders produced 281, 103, and 262 m^3/8-hour shift, respectively. In winter, the small crawler tractors produced 271 m^3/8-hour shift and the cable yarder produced 112 m^3/8-hour shift. Production per system hour, the amount of wood that each system (all machines and manpower) produced on an hourly basis, was used to compare the three systems. The small crawler-tractor system produced 34.2 m^3/system hour, compared to 32.9 m^3 for the conventional system and 13.3 m^3 for the cable system.

Seasonal differences in production appeared to be related more to effects of piece size than to weather. The average piece size was 0.89 m^3 (summer) and 0.70 m^3 (winter) for the cable system, and 0.73 m^3 (summer) for the conventional system.

Skidding and trail-building costs were $6.99/$m^3$ for the small crawler tractors and $6.61/$m^3$ for the conventional system, compared to a yarding, limbing, and bucking cost of $12.18/$m^3$ for the cable system. Organizational differences between logging systems complicate direct comparison of phase costs. The calculated cost for wood loaded onto the truck was $13.25/$m^3$ for the small crawler-tractor system, $11.34/$m^3$ for the conventional system, and $18.60/$m^3$ for the cable-yarding system.

Assuming that each logging system required equal proportions of truck roads and landings in relation to area logged, and using criteria established by the B.C. Ministry of Forests, detrimental soil-disturbance levels were calculated as: 18% (summer) and 12.6% (winter) for the small crawler-tractor system; 10% (summer) and 7.6% (winter) for the cable system; and 27.4% (summer) for the conventional system. For the small crawler-tractor system, significant increases in soil bulk density were recorded along the inner track of most summer and winter skid trails. Soils on heavily disturbed yarding roads of the cable system were not significantly denser than undisturbed soils. Not enough samples were collected from the conventionally logged area for statistical analysis.

McDonald, M.J. 1979. Development and evaluation of the critical site yarder. FERIC, Vancouver, B.C. Tech. Note No. TN-31. 30 p.

The study of the Critical Site Yarder started with industry-wide interest in a cable yarder suitable for logging on the steep sidehills and other environmentally sensitive areas of Interior B.C. Cottell *et al.* (1976) had studied a number of cable yarders in Interior B.C. and concluded that none of the machines studied was completely satisfactory for Interior conditions. Based on a consultant's advice, an Interior company converted an American Crane model 395 to a small 3-drum yarder.

Average production for 10 areas was 10.5 m^3/PMH with an average piece size of 0.50 m^3. Calculated yarding costs were $10.33/$m^3$ with a total cost on-truck of $15.24/$m^3$. Comparing production and cost estimates for this yarder with the machines examined in FERIC reports TR-8 and TN-19 (with costs adjusted to 1979 dollars) showed that the Washington 078 had the lowest cost on-truck at $9.75/$m^3$, followed by the Skagit GT3 at $10.75/$m^3$. All of the other machines were also less, with the exception of the $21.01/$m^3$ of the Mini-Alp, than the $15.24/$m^3$ of the Critical Site Yarder. The high cost of wood on the truck for the Critical Site Yarder was due to the low volumes yarded per shift.

McDonald, M.J. 1981. Evaluation of the Finning swing hydraulic yarder. FERIC, Vancouver, B.C. Tech. Note No. TN-40. 28 p.

This study examined and compared grapple-yarding operations of a prototype swing yarder, the Finning SY235, and a Skagit GT3. Both machines were grapple yarding with mobile backspars in the same area. Average piece size was 0.77 m^3. The Finning SY235 produced 34.9 m^3/PMH compared to 32.6 m^3/PMH for the Skagit GT3. Total cost of wood on the truck was calculated as $13.15/$m^3$ for the SY235 and $12.18/$m^3$ for the GT3. The Finning prototype's production was sufficient to meet its high ownership cost but its calculated yarding cost of $7.31/$m^3$ was greater than the $6.34/$m^3$ of a new Skagit yarder. Since the SY235 was a prototype machine, it was expected that its availability (72% compared to 84% for the GT3) would increase under normal operating circumstances.

McMorland, B.S. 1977. Evaluation of Volvo BM 971 clam bunk skidder. FERIC, Vancouver, B.C. Tech. Rep. No. TR-16. 43 p.

The results of a study involving a Volvo clam bunk skidder operating under clearcut and right-of-way conditions are reported. During the study, the skidder averaged 20.8 m^3/PMH under clearcut conditions, and 22.8 m^3/PMH on right-of-way skidding. Average piece size was 0.57 m^3 for both operations. Costs were estimated at $1.76 (high productivity, low total cost) to $5.05 (low productivity, high total cost) per cubic meter for the Volvo; and for wheeled skidders in the B.C. interior, ranged from \$1.54 to \$3.43/m³. Volvo costs were, therefore, similar, even though skidding distance was 2-5 times as far.

McMorland, B.A. 1978. The Skagit GT3 grapple yarder and the Igland-Jones Highland Trailer Alp. FERIC, Vancouver, B.C. Tech. Note No. TN-19. 11 p.

This report contains the study results of two cable-logging operations during 1976. The machines studied were a Skagit GT3 grapple yarder (an extension of FERIC report TR-8, Cottell *et al.* [1976] and an Igland-Jones Trailer Alp (Mini-Alp). The GT3 results confirm the TR-8 findings of this yarder's high production and low cost per cubic meter relative to other Interior cable-logging operations. Average production per productive machine hour was 38.1 m^3 (average piece size 0.96/m^3). The calculated yarding cost was \$3.98/m^3, and total cost on the truck was \$7.96/m^3. The Mini-Alp operated in small timber (average 0.31 m^3) on steep slopes. The Mini-Alp averaged 4.4 m^3/PMH. (This was attributed mainly to operating with an inexperienced crew. Time lost to delays was 66% of scheduled time). Yarding cost was calculated at \$11.52/m^3 with a total cost on truck of \$17.59/m^3.

McMorland, B.A. 1980a. Skidding with small crawler tractors. FERIC, Vancouver, B.C. Tech. Rep. No. TR-37. 89 p.

FERIC evaluated seven contractor-owned John Deere and International skidding tractors and one company-owned John Deere trailbuilder in the B.C. Interior for most of the 1977-1978 logging season. The tractors fell into two size ranges: between 63 and 65 hp (with blade widths ranging from 2.3 to 2.7 m), and between 72 and 78 hp (blade widths, 2.4 to 3.2 m). The contractor fleet averaged 8.1 m^3/PMH based on an average piece size of 0.49 m^3. The cost per cubic meter to fell trees and operate one small tractor as a skidding unit was calculated to be \$8.19/m^3.

Company records were used to compare costs of small tractors and rubber-tired skidders under similar stand and terrain conditions. Skidding costs were \$5.94/m^3 for small tractors and \$5.73/m^3 for rubber-tired skidders, while the total cost of decked logs was \$8.07/m^3 and \$8.86/m^3 for the small tractor and rubber-tired skidder respectively.

Comparable costs were \$9.73 for an FMC bunk grapple skidder (Powell 1987) and \$20.87/m^3 for a 3-drum cable yarder (McDonald 1979). However, stand and terrain conditions for these two studies did not match those of the crawler-tractor and wheeled skidder systems.

Small crawler tractors resulted in a reduction of total site disturbance, regardless of depth, of approximately one-third compared to larger crawler tractors. The percentage of site disturbance caused by roads, landings, and logging activity was similar for small and large tractor cutblocks, but skid trail-related disturbance was considerably lower (by approximately one-half) on the blocks logged by the small machines for both summer and winter conditions.

McMorland, B.A. 1980b. Non-shearing felling heads. FERIC, Vancouver, B.C. Technical Note No. TN-34. 48 p.

The results of studies on five chainsaw felling heads and one rotary cutter (auger) in the north-central interior of B.C. are combined and summarized in this report. Machine descriptions, production figures, and butt damage results are presented for all six machines (Albright Buncher, Albright Director, Dika Buncher, Dika Director, Drott Auger Buncher, Northwood/FERIC Director). Direct comparisons between machines were difficult to make because of differences in operating conditions and varying stages of development among the machines.

McMorland, B.A. 1984. Production and performance of mechanical felling equipment in Interior B.C.: Harricana circular saw. FERIC, Vancouver, B.C. Tech. Note TN-74. 11 p.

FERIC studied a Harricana circular saw feller buncher (Drott 40 carrier) in four cutting areas with a maximum slope of 25%. Production averaged 44.7 m^3, or 102 trees per PMH. Since the study, improvements made to both the carrier and head should reduce repair and service time. No cost information was reported.

McMorland, B.A. 1985. Production and performance of ground skidding equipment in Interior B.C.: FMC FT-180/John Deere 550 system. FERIC, Vancouver, B.C. Tech. Note No. TN-82. 20 p.

This report presents the results of a ground-skidding study involving an FMC FT-180 Fast Track log skidder and a John Deere 550 crawler tractor. The main objective of the study was to determine if an FT-180/small tractor combination could be an alternative system to cable logging on slopes of 30-55%. The first of two areas studied had sidehill slopes between 35 and 60% and an average tree volume of 0.4 m^3. The second area was right- of-way road access with a maximum slope of 9% and an average tree volume of 1.7 m^3. The FMC was used for skidding as much as possible, while the tractor also performed trail building, decking, and landing cleaning. The FMC averaged 8.0 and 17.1 m^3/PMH in the clearcut and right-of-way areas, respectively, and the JD550 tractor averaged 5.2 and 11.4 m^3/PMH in the same areas, respectively, for a total system productivity of 13.2 m^3/PMH for the clearcut and 28.5 m^3/PMH for the right-of-way. No costs or site-disturbance levels were reported. The author stated that the FMC FT-180 appeared to be best suited to situations where its speed, gradability, or flotation could be utilized to advantage. Such conditions include long skid distance (200-500 m); ground slopes of up to 55%; and swampy or sensitive sites.

McMorland, B.A. 1986. Production and performance of mechanical felling equipment in Interior B.C.: Timbco feller-buncher with Rotosaw head. FERIC, Vancouver, B.C. Tech. Rep. No. TR-67. 22 p.

This report analyzes the Timbco Model 2520 feller buncher, which has the ability to bunch trees on slopes of 30-50 percent. This study took place on a site with an average tree volume of 0.86 m^3 and approximately 5% of the block exceeding 30% slope. The Timbco averaged 378 trees (32 m^3) per 8-hour shift or 69.9 trees (60.1 m^3) per productive machine hour. Harvesting costs and skidder performance were not reported.

Powell, L.H. 1978. Production and performance studies of FMC 200 series skidders. FERIC, Vancouver, B.C. Tech. Rep. No. TR-29. 37 p.

This report presents the results of a 2-year study evaluating the performance of 6 FMC skidders under various terrain and operating conditions in B.C. Four studies took place in the Interior and two on the Coast. Two models were evaluated: the 200 BG bunk grapple skidder and the 200 CA choker arch skidder. In the B.C. Interior, the 200 BG averaged 15 m^3/PMH (0.48 m^3/piece) while the average production of the 200 CA ranged from 18.6 m^3 (1.30 m^3/piece) to 23.6 m^3 (2.41 m^3/piece) per PMH. Production figures indicated that the 200 BC may be expected to achieve productivities of between 17 and 20 m^3/PMH with a potential of up to 25 m^3/PMH for the 200 CA. Skidding costs were estimated at \$4.96/m^3 for the 200 BG and \$2.71 - \$3.66/m^3 for the 200 CA.

Visual inspections of skidded areas indicated that soil disturbance was not considered to be a problem. The author concluded that the FMC skidders would allow the range of ground skidding to be extended into the 30-50% slope range while still meeting production and environmental requirements.

Powell, L.H. and D.W. Myhrman. 1977. Evaluation of Earls ParaShear feller-buncher. FERIC, Vancouver, B.C. Tech. Rep. No. TR-17. 45 p.

FERIC studied two versions of the ParaShear feller buncher, which is a feller buncher attachment for any tractor or excavator undercarriage. Under summer conditions, the machine's productivity averaged 32 m^3/PMH (average 0.42 m^3/tree) and in winter averaged 24 m^3/PMH (average 0.32 m^3/tree). Costs for felling and bunching were estimated at \$1.33/m^3 under favourable conditions to \$4.88/m^3 under unfavourable conditions.

Powell, L.H. and G. St. Jean. 1979. Trial of OSA 670 feller buncher and OSA processor in British Columbia. FERIC, Vancouver, B.C. Tech. Rep. No. TR-31. 58 p.

An OSA 670 feller buncher and an OSA 705 processor were assessed under various B.C. Interior terrain and operating conditions. The OSA 670 was designed for steeper slopes (up to 45%) and larger trees (up to 56 cm). The OSA 670 averaged 28.4 m^3/PMH (67 trees/PMH) under conditions of steep rough terrain and average volume per tree of 0.42 m^3. Under gentle slope conditions and average tree size of 0.71 m^3, the machine averaged 59.5 m^3/PMH (91 trees/PMH). Total trial average was 38.1 m^3/PMH (69 trees/PMH).

Production on steeper slopes was lower, but the machine was able to work in areas where other available feller bunchers could not operate.

Calculated operating costs ranged from $1.44/m^3 under favourable conditions to $5.60/m^3 under unfavourable conditions. Detailed surveys of site disturbance were not performed on the harvested areas because disturbance levels observed were considered to be acceptable.

Ruault, R.E. 1982. Surface systems approach to handling small timber on critical sites. *In* The small tree resource: a materials handling challenge. For. Products Res. Soc., Madison, WI. Proc. 7306. pp. 129-135.

Presents the planning system (''Total Chance Concept'') of a B.C. Interior company to harvest small timber on critical sites. Nine different harvesting systems for the Nelson Forest Region are summarized according to operating constraints of the system, the expected productivity, and the equipment and manpower required.

Waelti, H. 1976. Long reach skylines. *In* Proc. of the Skyline Logging Symp., Vancouver, B.C.

This paper presents the characteristics, applications, and planning of long reach skylines. A 5-month operation using a Wyssen W90 model yarder with 4000 ft (1220 m) of skyline was monitored during 1974 and 1975 near Nelson, B.C. The operation averaged 18.8 turns/9-hour day (3.9 m^3 or 3.2 logs/turn). No costs were reported.

Wellburn, G.V. 1975. Alternative methods for logging steep slopes in the Nelson Forest District of British Columbia. Environ. Can., For. Manage. Inst., Ottawa, ONT. Inf. Rep. FMR-4-76.

This report contains a comparison of the productivity and expected cost for different machines in use in the Nelson Forest District (1975). Three areas, all with slopes greater than 50%, were examined and costs determined for different harvesting methods.

CHAPTER III
ECONOMIC IMPACTS OF SOIL DEGRADATION

1 SUMMARY

The economics of soil disturbance has received very little attention in the literature to date. The science of economics certainly has the tools to analyze this problem, as the methodology required is no different than that used in the analysis of a silvicultural investment or a forest land alienation problem. Rather, the problem has received little attention because of the difficulty in obtaining appropriate data on the productivity impacts of site disturbance, the values of off-site impacts, and other pertinent information.

The failure of the forest economics community to spell out an appropriate paradigm for soil disturbance problems has resulted in a variety of approaches to the problem, some of them ad hoc. Several of the papers reviewed below call for further research into the economics of soil disturbance. This is a clear and pressing need. Just as a standardized approach is being developed for biological analysis, so one must be developed for economic analysis. The major conclusions of the reviews are:

1. Alternative logging systems should be analyzed over all entries in a rotation to determine which is truly least cost when all factors are considered.
2. Pre-logging assessment of on-site and downstream erosion impacts may show that environmentally acceptable advance systems of yarding could cost less than traditional systems at some locations.
3. Taking into account downstream and on-site benefits and costs of the decision to log or not log sensitive sites, the manager can determine the landslide risk threshold and achieve the greatest net benefit from a timber harvest.
4. Forest land practices must be sensitive to slope processes to avoid the consequences of mass wasting. Where, in spite of our best intentions, mass wasting occurs, efforts should focus on mitigation and rehabilitation.
5. The high cost of endhauling suggests that sideslope, gradient, endhaul distance, steep road alternatives, slide risk, and expected slide damage must be considered simultaneously in choosing the most economical road design.
6. Harvest plans need to take into account the possible future impacts of soil compaction. The discount rate and site index are also important factors in determining the justifiable increase in yarding cost to avoid the effects of soil compaction.
7. The problem of soil degradation in B.C. can best be met by better planning. Planning, taking into account all values at risk, is cost-effective and less expensive than rehabilitation. Risk of failure needs to be incorporated in any analysis of site rehabilitation projects.
8. Soil conservation is not likely to be attractive to a private owner of forest land. Even a moderate discount rate can encourage poor soil management practices. Sustained yield forestry reaches substantially different conclusions. The discount rate is shown to have an important influence on the value placed on acceptable productivity losses due to soil degradation.

2 ANNOTATED LITERATURE

Bowden, G.K. 1988. Economics of forest soil degradation and rehabilitation. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 217-222.

The effects of soil degradation are separated into external effects such as water quality and other off-site effects, and internal effects such as the reduced productivity of the site for successive crops. The economist would suggest that this problem could be easily solved if greater harvesting costs were incurred today up to the point where these costs meet the resulting benefits. Doing this, however, is not feasible given the existing data base. Regulation is often used when economic solutions are not workable, these solutions are sometimes inefficient. Current regulations employed to mitigate the negative impacts of logging are reported to be about $10/m^3$. This implies that about $700 million in benefits should be accruing annually as a result of these efforts. It is debatable whether this level of benefits is being achieved, and the problem merits further study.

The specific problem of site degradation can be analyzed using a net present value (NPV) analysis which discounts future losses to the present day to determine what we can afford to spend today to mitigate these losses. Forecasting these losses and their value and determining an appropriate discount rate hamper efforts in this direction. Further research is recommended. A second approach is to reduce current AAC to offset the future impacts of lost productivity. Although the value of this loss is more easily quantifiable, this approach is not considered to be ''economically prudent.''

Donnelly, D.M. 1977. Estimating the least cost combination of cable yarding and tractor skidding for a timber sale area. USDA For. Serv. Res. Note RM-341. Mimeo. 8 p.

The topography of an area to be logged was analyzed to classify areas by percentage of slope. Six technically feasible combinations of roads, cable yarding, and tractor skidding were examined. The least-cost alternative was determined using a discounted NPV methodology over 7 treatment entries in a 120-year period. The analysis demonstrated that increased soil protection costs in terms of higher road standards may lead to cable yarding becoming a less expensive alternative than the apparently less costly tractor skidding.

Hammond, H.L. 1988b. Soil degradation: costs of rehabilitation versus costs of prevention. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 227-237.

Long-term soil degradation is primarily caused by forest road construction and machine activity. Degradation reduces site productivity but exact volume losses over a rotation are not known. Costs associated with site degradation include those for: reconstruction of failed roads, restocking, increased fertilizer applications, reduced timber values, tillage, and other rehabilitation costs which can range from $2500 to $4000/ha. Damage to fish habitat, domestic and agricultural water supplies, aesthetics, and other off-site items adversely affected by degraded soil must also be included in the harvesting decision.

The high cost of rehabilitating the effects of soil degradation leads one to investigate how such losses could be prevented in the first place. The literature is clear that prevention is less expensive than rehabilitation. Prevention in the form of holistic planning which takes into account all forest values both on and off site is the most cost-effective means to control soil degradation. Comprehensive planning costs ($200-$400/ha) will be less than the costs of lost timber production and environmental damage caused by soil degradation.

Klock, G.O. 1976. Estimating two indirect logging costs caused by accelerated erosion. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland OR. Gen. Tech. Rep. PNW-44. 8 p.

In areas where there is high potential for soil erosion, the resulting indirect costs should be added to the direct logging cost to compare the total costs of alternative logging systems. Two examples are provided: loss of site productivity and reservoir sedimentation. Fertilizer costs to bring the site back to its former productivity and the cost of sediment removal are estimated based on the level of erosion and added to the direct logging cost. In the examples provided, this results in logging systems which have a higher direct cost but which cause less erosion, being chosen over systems which have lower direct cost but cause more soil degradation.

Rice, R.M., N.H. Pillsbury, and K.W. Schmidt. 1985. A risk analysis approach for using discriminant functions to manage logging-related landslides on granitic terrain. For. Sci. 31: 772-784.

A portion of the paper describes a procedure that can be used to determine how to log slide-prone slopes. The manager must decide on the resource and environmental penalties and benefits associated with the consequences of various correct and incorrect site classifications. The optimum risk of slide that the manager can accept based on these consequences is chosen to maximize the expected return from the harvest area.

Routledge, R.D. 1988. Assessing long-term costs of forest soil degradation. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 223-226.

A soil expectation value (SEV) analysis is used to examine the strength of economic incentives for the private landowner to maintain future site productivity. The SEV analysis has been criticized because it assumes that future rotations will behave just like the first one. A dynamic programming technique is used to assess the consequences of declines in productivity caused by the construction of skidroads and landings. A private landowner with a high discount rate (10%) is shown to have little concern about a permanent reduction in soil productivity because future harvests are almost worthless compared to the value of today's harvest. When a 2% discount rate is used, the incentive increases only slightly. When a site is managed for maximum sustained yield, future rotations cannot be ignored and the incentive is increased. This method is equivalent to using a zero discount rate.

Routledge, R.D. 1987. The impact of soil degradation on the expected present net worth of future timber harvests. For. Sci. 33 (4): 823-834.

Adjustments are made to the traditional Faustmann soil expectation value formula to account for soil degradation. A dynamic programming algorithm is developed to assess direct, long-term losses associated with destructive logging practices. The discount rate is shown to have an important influence on what acceptable value could be placed on productivity losses due to soil degradation.

Schwab, J.W. 1988. Mass wasting impacts to forest land: forest management implications, Queen Charlotte timber supply area. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 104-115.

A section of the paper is devoted to estimating the loss in annual economic activity in the Queen Charlotte TSA resulting from mass wasting. The direct cost is estimated by calculating stand investment (plantation establishment, surveys, etc.), productivity declines, and regeneration delay. Indirect costs are estimated for a worst-case scenario that results in accelerated failure rates. Timber losses of $19.7 million at rotation within the Rennell Sound area are projected and when this is extrapolated over the entire Queen Charlotte TSA, losses are estimated at $242 million at rotation. The AAC would be reduced by 15165 m^3/yr or $3 million in economic activity annually.

Sessions, J., J.C. Balcom, and K. Boston. 1987. Road location and construction practices: effects on landslide frequency and size in the Oregon Coast Range. West. J. Appl. For. 2(4): 119-124.

Reductions in landslide frequency and volumes can be obtained if careless construction practices are considered and more expensive road construction methods are used. The costs associated with reducing landslide volumes can be derived from estimates of landslide volume with different road designs and the difference in road construction and hauling costs. Where slide frequency was low, the estimated cost of slide prevention on a cubic yard basis was very high. Steeper road grades to minimize road mileage on steep sideslopes and endhaul of excavated material on sideslopes of greater than 50% were identified as major techniques to reduce slide frequency and volume. Steep road grades were found to be more cost effective. The appendices include some sample calculations.

Stewart, R., H. Froehlich, and E. Olsen. 1988. Soil compaction: an economic model. West. J. Appl. For. 3(1): 20-22.

A microcomputer model is developed to assess the impact of compaction on stand productivity under different harvest specifications. The effect of varying skid trail spacing on NPV is investigated. The NPV analysis is used to determine the increased cost which is justifiable to eliminate the effects of soil compaction. The implications of low initial site indices and changes in the discount rate are also investigated. The model links forest productivity with economic benefits to find the economic cost of single- or multi-entry harvest plans. The program determines volume yield for a harvest entry, impact of the entry, and the site index to be used for subsequent growth periods. Finally, changes in the management plan (e.g., different skid trail spacing) are related to changes in the production rate of the harvest system. Values obtained from this part of the model are applied to timber yields of a given site, and to harvest and transportation costs. All benefits and costs are adjusted to present values.

Sullivan, J., P.N. Omi, A.A. Dyer, and A. Gonzales-Caban. 1987. Evaluating the economic efficiency of wildfire rehabilitation treatments. West. J. Appl. For. 2(2): 58-61.

The NPV and benefit cost (B/C) are economic efficiency criteria used by the USDA Forest Service for evaluating rehabilitation projects. Treatments are often applied with little consideration of the risk of failure. A decision-tree approach allows for the incorporation of risk through the calculation of expected NPV's and B/C's. Application of this technique to documented projects in the Pacific Northwest and Rocky Mountain areas revealed that risk was generally not considered and the economic efficiency of nearly all rehabilitation projects was suspect.

White, W.A. 1988. A method for assessing the economic impacts of soil disturbance. Can. For. Serv., Pac. For. Cent., Victoria, B.C. Unpubl. Economics Rep. 23 p.

The appropriate methodology for addressing questions of soil degradation depends on the objectives of the decision-maker and the constraints he faces. A private firm interested only in financial return may consider only financial variables. The Crown, responsible for managing land in the public interest, would consider a wider range of variables, including off-site costs. To bring the private and public solutions together, the government can regulate the behaviour of private firms, although this is not always desirable since increased costs to firms can effectively reduce the economic timber supply.

The ideal solution to the soil disturbance problem will come through cost-effective prevention or rehabilitation mechanisms. These would be more willingly accepted by private firms, and would reduce or eliminate the timber supply impacts. A present, pre-harvest planning shows the most potential in this area. Developments of low-cost, low-impact harvesting and rehabilitation systems may also prove to be cost-effective means of reducing the undesirable effects of soil disturbance.

This paper displays, within a linear programming (LP) framework, a variety of approaches to the economics of soil disturbance. It discusses the context in which each decision-maker may allocate resources in an economically efficient manner and measure the economic impact of soil disturbance resulting from the harvesting or policy decisions made.

Linear programming is an appropriate framework for solving problems which require the choice of one of a mutually exclusive set of alternatives. It is very flexible because the objective function and the constraints can be modified to supply solutions specific to the goals and constraints of various decision-makers. Sensitivity analysis is provided with LP solutions to show how the optimal solution will vary as costs and benefits change.

CHAPTER IV
RESEARCH NEEDS

Available research information from other areas in the Pacific Northwest is useful in helping B.C. land managers address land degradation issues. However, the most useful information available to us is that generated within B.C. through the limited research effort which has been undertaken. These local studies are obviously relevant to B.C.'s site conditions, forest management philosophy, and forestry practices, and, therefore, have more credibility and acceptance. It is thus imperative that we make the administrative and financial commitments both to undertake the research to solve the soil degradation/forest productivity problems we have, and to ensure that the information generated is adequately disseminated and appropriately implemented.

Two recent reviews of soil degradation research needs in B.C. have been completed. (Still 1988; Walmsley *et al*. 1988). Both reviews were comprehensive lists of research needs categorized into larger priority areas. Because these lists are so comprehensive, this report highlights only what might be considered the highest priority needs. While this section of our report is entitled "Research Needs," there are other needs, particularly in the areas of planning and extension, which are ranked highly as well. With the indulgence of the aforementioned authors, the following list is proposed as representing the highest priority (unranked) needs related to the problems of soil degradation/site productivity relationships.

1. There is a need to develop extension programs which deal with: the concept of soil as a manageable resource, fundamentals of applied soil science, the concepts of soil and site productivity, the visible impacts of soil degradation, the subtle impacts of soil degradation, and the mitigative and rehabilitative measures which are available. The target audience for these extension programs would be timber management, engineering, and silviculture operations staff in industry and government; and harvesting, logging, engineering and silviculture contractors.
2. To predict site sensitivities reliably and to develop appropriate management prescriptions, there is a need to provide inventory data and interpretations through the biogeoclimatic ecosystem classification program and site analysis.
3. There is a need to develop, test, and implement simple, quick and reliable methods for estimating and monitoring soil disturbance.
4. There is a need to establish research installations which will be the sites of long-term assessments of soil and productivity changes caused by forest management activities, particularly site preparation.
5. There is a need to examine the effectiveness and costs of using planned and designated skid trails to reduce soil degradation.
6. There is a need to examine the factors affecting the long-term tree growth on or adjacent to roads and landings.
7. There is a need to develop guidelines for the selection of sites for soil rehabilitation; that is, to determine the possibility of minimizing productivity losses.
8. There is a need to test the short- and long-term effectiveness of rehabilitation strategies and techniques by measuring subsequent tree growth and productivity.
9. There is a need to develop a standardized approach and methodology for the analysis of the economic impacts of soil degradation.
10. There is a need to analyse the economic impacts of the various aspects of soil degradation, the economics of soil and site rehabilitation, the economics of pre-harvest planning, and the economics of mitigating on-site and off-site impacts.

11. There is a need to assess the operating costs, machine productivity, and site impacts of harvesting equipment and systems appropriate for use in the range of site and climate conditions encountered in the interior of British Columbia.

Research cannot provide all the necessary answers as we move increasingly into more sensitive forest lands and face future timber supply falldowns. Because financial support for research is limited, there is a greater return to be realized if available funds could be spent first on the development of an extension program. Changing attitudes and increasing the level of awareness amongst field staff and operators would substantially reduce on- and off-site impacts of forest harvesting and renewal.

CHAPTER V: APPENDIX

LIST OF REFERENCES RELEVANT TO INTERIOR BRITISH COLUMBIA

ADAMS, P.W. 1979. Recognizing and measuring soil compaction. Soil Air & Water Notes. USDA For. Serv. North. Region. Soil Air & Water Notes. 9 p.

________ 1983. Recognizing and measuring soil compaction. *In* Forest soil compaction: problems and alternatives. Oreg. State Univ., For. Engineer. Short Course, Corvallis, OR. 19 p.

ADAMS, P.W. and H.A. FROEHLICH. 1981. Compaction of forest soils. USDA For. Serv., Pac. NW Extens. Publ. PNW 217. 13 p.

ADAMS, P.W., J.J. GARLAND, and H.A. FROEHLICH. 1985. Research and extension programs lead to effective management of forest soil compaction in the Pacific Northwest. *In* Foresters' future: leader or followers. Proc. 1985 SAF Nat. Conv., Fort Collins, CO. pp. 121-124.

AGRICULTURAL INSTITUTE OF CANADA. 1985. A strategy for soil and water conservation in Canada. Presentation to the House of Commons Committee on Agriculture. AIC, Ottawa, ONT.

ALDRICH, J.W. and C.W. SLAUGHTER. 1983. Soil erosion on subarctic forest slopes. J. Soil Water Conserv. 38 (2): 115-118.

ALYMORE, L.A. and I.D. SILLS. 1978. Pore structure and mechanical strength of soils in relation to their constitution. *In* Modification of soil structure. W. W. Emerson *et al.* (editors). John Wiley & Sons, New York, NY. pp. 69-78.

AMARANTHUS, M. and D.H. McNABB. 1983. Bare soil exposure following logging and prescribed burning in southwest Oregon. *In* New Forests for a Changing World. Proc. 1983 SAF Nat. Conv. pp. 234-237.

AMARANTHUS, M.P., R.M. RICE, N.R. BARR, and R.R. ZIEMER. 1985. Logging and forest roads related to increased debris slides in southwestern Oregon. J. For. 83: 229-233.

ANDERSON, C.H. 1977. Methods of reducing capital cost of logging equipment suited for harvesting Interior timber types in British Columbia. Report prepared for the Forest Engineering Research Institute of Canada. 93 p.

ANDRUS, C.W. and H.A. FROEHLICH. 1983. An evaluation of four implements used to till compacted forest soils in the Pacific Northwest. Oreg. State Univ., For. Res. Lab., Corvallis, OR. Res. Bull. 45. 12 p.

ANONYMOUS. 1977. Small tractors, skidding "steep" slopes. B.C. Logging News. May 1977. pp. 894-896.

________ 1980. Soil compaction, regional interim guidance. Region 1. USDA For. Serv. 5 p.

________ 1982. Proposed technical guide - soil compaction - draft. Tally Lake Ranger District. USDA For. Serv. 8 p. and appendices.

________ 1983. Soil monitoring results: Malheur National Forest, 1982 and 1983 Program. USDA For. Serv. 13 p. and appendices.

________ 1985. A guide to prescribed broadcast burning in the Vancouver Forest Region. B.C. Min. For., Vancouver, B.C. and MacMillan Bloedel, Nanaimo, B.C. 110 p.

________ 1987a. Better harvesting practices for protecting forest soil. B.C. Min. For. Lands, Silv. Br., Victoria, B.C. 29 p.

________ 1987b. Ground skidding guidelines with emphasis on minimizing site disturbance. B.C. Min. For. Lands, Engineer. Br. and Silv. Br., Victoria, B.C. 58 p.

ARNOTT, J.T., W.W. CARR, and A.C. WAINES. 1988. Establishing forest cover on winter landings in the central interior of British Columbia. For. Chron. 64 (2): 121-126.

ASSOCIATION OF BRITISH COLUMBIA PROFESSIONAL FORESTERS. 1985. Economic benefits of timber and productive forest land in British Columbia: a position paper. 17 p. and appendices.

AULERICH, D.E., K.N. JOHNSON, and H.A. FROEHLICH. 1974. Tractors or skylines: what's best for thinning young-growth Douglas-fir. For. Industries, Nov. 1974.

BALLARD, R. 1977. Effect of slash and soil removal on the productivity of second rotation radiata pine on a pumice soil (R1078, Kaingaroa S. F.). N. Z. J. S., For. Res. Inst. Soils and Site Productivity Rep. No. 86. 24 p.

BALLARD, T.M. 1983a. Soil degradation effects of forest harvesting and site preparation. *In* Soil degradation in British Columbia. Proc. 8th B.C. Soil Sci. Workshop. B.C. Min. Agric. Food, Victoria, B.C. pp.166-176.

———— 1983b. Forest soils and tree nutrition. *In* Forestry handbook for British Columbia. 4th ed. S.B. Watts (editor). Univ. B.C., Fac. For., For. Undergraduate Society, Vancouver, B.C. pp. 207-219.

———— 1984a. Forest soils considerations in site preparation. SISCO Summer Workshop, Fernie, B.C. Unpubl. 12 p.

———— 1984b. Nutrition of planted white spruce. Contract Res. Rep., B.C. Min. For. 23 p. and appendices.

———— 1985. Effects of burning and mechanical site preparation on nutrition of planted white spruce. Contract Res. Rep., Can. For. Serv. Pac. For. Res. Cent., Victoria, B.C. 78 p.

———— 1988. Soil degradation associated with forest site preparation. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 74-81.

BALLARD, T.M. and R.P. WILLINGTON. 1975. Slope instability in relation to timber harvesting in the Chilliwack Provincial Forest. For. Chron. 51 (2): 59-62.

BARKER, J.E. 1982. The effects of slash burning on nutrient concentrations of higher elevation soils at Jordan River. Western Forest Products. Final Rep., Proj. WFP 25-003. 13 p.

BARLEY, E.P. and E.L. GREACEN. 1967. Mechanical resistance as a soil factor influencing the growth of roots and underground shoots. Adv. Agron. 19: 1-43.

B.C. MINISTRY OF FORESTS AND LANDS. 1986. Interior end-product appraisal manual. Victoria, B.C.

BEESE, W.J. 1986a. Effects of prescribed burning on some coastal B.C. sites. MacMillan Bloedel Ltd., Nanaimo, B.C. 14 p.

———— 1986b. Reforestation of debris slides. Prog. Rep. Proj. 120.5. MacMillan Bloedel Ltd., Nanaimo, B.C. 11 p.

BELL, M.A.M., J.M. BROWN, and W.F. HUBBARD. 1974. Impact of harvesting on forest environments and resources. Can. For. Serv., Ottawa, ONT. For. Tech. Rep. 3. 237 p.

———— 1975. Impact of harvesting on forest environments and resources. A review of literature and evaluation of research needs. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Contract Rep. OSP3-O41O. 141 p.

———— 1976. Impact of harvesting on forest environments and resources. Can. For. Serv., Ottawa, ONT. Suppl. to For. Tech. Rep. 3. 15 p.

BERG, P.J. 1975. Development in the establishment of second rotation radiata pine at Riverhead Forest. N. Z. J. For. 20: 272-282.

BERGLUND, E.R. 1978. Seeding to control erosion along forest roads. Oreg. State Univ. Extens. Serv. Extens. Circ. 885. 19 p.

BLAKE, G.R., W.W. NELSON, and R.R. ALLMARAS. 1976. Persistence of subsoil compaction in a Mollisol. Soil Sci. Soc. Am. Proc. 40: 943-948.

BLAKENEY, K.J. 1980. Development and testing of a field treatment system for logging residues. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-X-212. 70 p.

BLOOMBERG, W.J., P.M. CUMBERBIRCH, and G.W. WALLIS. 1980a. A ground-survey method for estimating loss caused by *Phellinus weirii* root rot. I. Development of survey design. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-R-3. 23 p.

——— 1980b. A ground-survey method for estimating loss caused by *Phellinus weirii* root rot. II. Survey procedures and data analysis. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-R- 4. 44 p.

BOATENG, J.O. 1984. Estimates of forest brush problems in British Columbia. B.C. Min. For., Victoria, B C. Silv. Br. 16 p. and appendices.

BOCKHEIM, J.G., T.M. BALLARD, and R.P. WILLINGTON. 1975. Soil disturbance associated with timber harvesting in southwestern British Columbia. Can. J. For. Res. 5(2): 285-290.

BOCKHEIM, J.G., T.M. BALLARD, R.P. WILLINGTON, and J.L. LARSON. 1973. Impact of clearcutting on soils and watersheds, southwestern British Columbia. Dep. Environ., Victoria, B.C. 230 p.

BODMAN, G.B. and G.K. CONSTANTIN. 1965. Influences of particle size distribution on soil compaction. Hilgardia 36: 567-591.

BORMANN, F.H., G.E. LIKENS, D.W. FISHER, and R. S. PIERCE. 1968. Nutrient loss accelerated by clear-cutting of a forest ecosystem. Science 159: 882-884.

BOURGEOIS, W.W. 1978. Timber harvesting activities on steep Vancouver Island terrain. *In* Forest soils and land use. Proc. 5th N. Am. For. Soils Conf. Col. State Univ., Dep. For. Wood Sci., Fort Collins, CO. pp. 393-409.

BOWDEN, G.K. 1988. Economics of forest soil degradation and rehabilitation. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 217-222.

BOYER, D. 1979. Guidelines for soil resource protection and restoration for timber harvest and post-harvest activities. USDA For. Serv., Pac. NW Region Watershed Manage. 43 p. and appendices.

BOYLE, J.R. and A.R. EK. 1972. An evaluation of some effects of bole and branch pulpwood harvesting on site macronutrients. Can. J. For. Res. 2: 407-412.

BRAATHE, P. 1973. Prescribed burning in Norway; effects on soil and regeneration. Tall Timbers Fire Res. Conf. Proc. 13: 211- 222.

BRADFORD, J.M. and R.B. GROSMAN. 1982. *In-situ* measurements of near-surface soil strength by the fall-cone device. Soil Sci. Am. J. 46: 685-688.

BRADSHAW, G. 1979. Preplanned skid trails and winching versus conventional harvesting on a partial cut. Oreg. State Univ., For. Res. Lab., Corvallis, OR. Res. Note 62. 4 p.

BREADON, R.E. 1983. Timber development planning for the British Columbia interior: the total-chance concept. FERIC, Vancouver, B.C. Handb. 4. 73 p.

BURGER, J.A., J.V. PERUMPRAL, R.E. KREH, J.L. TORBERT, and S. MINAEI. 1985. Impact of tracked and rubber-tired tractors on a forest soil. Trans. ASAE 28 (2): 369-373.

BURROUGHS, E.D., JR. and B.R. THOMAS. 1977. Declining root strength in Douglas-fir after felling as a factor in slope stability. USDA For. Serv., Intermount. For. Range Exp. Sta. Res. Paper INT-190. 27 p.

BUTT, G. 1987. Effects of skidder compaction on tree productivity. MacMillan Bloedel Limited, Nanaimo, B.C. Unpubl. Rep. 62 p.

BUTT, G. and T. ROLLERSON. 1988. Prediction of forest soil compaction. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 153-166.

CANNELL, R.Q. 1977. Soil aeration in relation to root growth and soil management. Appl. Biol. 1977 (2): 1-86.

CANTLON, J. 1986. Summary of steep slope logging/site degradation review by the Kamloops TSA sub-committee to April 1986. B.C. Min. For., Clearwater, B.C. 21 p.

CARLISLE, A. and L. CHATARPAUL. 1984. Intensive forestry: some socio-economic and environmental concerns. Can. For. Serv., Petawawa Nat. For. Inst. 40 p.

CARR, W.W. 1980. Handbook for forest roadside erosion control in B.C. B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 4. 43 p.

_________ 1983. Access road related degradation problems in forestry. *In* Soil degradation in British Columbia. Proc. 8th B.C. Soil Sci. Workshop. B.C. Min. Agric. Food, Victoria, B.C. pp. 177-191.

_________ 1985a. Restoring productivity on severely degraded forest soils in British Columbia. Ph.D. thesis. Univ. B.C., Fac. For., Vancouver, B.C. 132 p. and appendices.

_________ 1985b. Watershed rehabilitation options for disturbed slopes on the Queen Charlotte Islands. B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 36. 35 p.

_________ 1986a. Assessment of landing rehabilitation activities in the Prince George East Forest District. B.C. Min. For., Prince George, B.C. Unpubl. Contract Rep. 14 p. and appendices.

_________ 1986b. Evaluation of ripping effectiveness of a winged subsoiler for soil decompaction in the Prince George East Forest District. B.C. Min. For. Lands, Prince George, B.C. 10 p.

_________ 1986c. Soil reconstruction on landing areas in the Mackenzie Forest District - BCFP. Unpubl. Interim Rep. B.C. Min. For., Prince George, B.C. 12 p.

_________ 1986d. Soil reconstruction on landing areas in the Prince George West Forest District - Lakeland Mills Ltd. B.C. Min. For., Prince George, B.C. Unpubl. Interim Rep. 10 p.

_________ 1987a. Restoring productivity on degraded forest soils: two case studies. FRDA Rep. 002. 21 p.

_________ 1987b. The effect of landing construction on some forest soil properties: a case study. FRDA Rep. 003. 20 p.

_________ 1988. The rehabilitation of degraded forest soil in British Columbia: an overview. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 197-203.

CARR, W.W. and T.M. BALLARD. 1980. Hydroseeding forest roadsides in British Columbia for erosion control. J. Soil Water Conserv. 35 (1): 33-35.

CARR, W.W. and W.R. MITCHELL. 1986. Timber harvesting disturbance on steep slopes: effects on soil properties and forest production. B.C. Min. For. Lands, Kamloops, B.C. Unpubl. Interim Proj. Rep. 26 p.

_________ 1987. Timber harvesting disturbance on steep slopes. *In* Proc. Workshop on Maintenance of Long Term Forest Productivity. Oreg. State Univ., Corvallis, OR. Abstract.

CARR, W.W., R. FRANK, and S. NORMAN. 1985. Effects of soil compaction on forest productivity and an annotated bibliography. Terrasol, Vancouver, B.C. Unpubl. Rep. 14 p.

CARR, W.W., W.R. MITCHELL, and W.J. WATT. 1988. Basic soil interpretations for pre-harvest silviculture planning: surface soil erosion, soil compaction. Terrasol, Vancouver, B.C. Unpubl. Rep. 34 p.

CARTER, M.C., J.W. MARTIN, J.E. KENNAMER, and M.K. CAUSEY. 1975. Impact of chemical and mechanical site preparation on wildlife habitat. *In* Forest soils and forest land management. B. Bernier and C.H. Winget (editors). Proc. 4th N. Am. For. Soils Conf. Les Presses de l'unversite Laval, QUE.

CASTILLO, S.R., R.H. DOWDY, J.M. BRADFORD, and W.E. LARSON. 1982. Effects of applied mechanical stress on plant growth and nutrient uptake. Agron. J. 74: 256-257.

CHAMBERLIN, T.W. 1972. Interflow in the mountainous forest soils of coastal British Columbia. *In* Mountain geomorphology: geomorphological processes in the Canadian Cordillera. O.Slaymaker and H.J. McPherson (editors). Tantalus Research Ltd., Vancouver, B.C. Geogr. Ser. 14. pp. 121-127.

CHAMBERLIN, T.W. and W.W. JEFFREY. 1968. Soil movement-water quality deterioration associated with timber harvesting in the West Kootenay area. Univ. B.C., Fac. For., Vancouver, B.C. Misc. Publ. 4.

CHANCELLOR, W.J. 1977. Compaction of soil by agricultural equipment. Univ. Calif., Div. Agric. Sci., Richmond, CA. Bull. 1881. 53 p.

CLAYTON, J.L. 1981. Soil disturbance caused by clearcutting and helicopter yarding in the Idaho batholith. USDA For. Serv., Intermount. For. Range Exp. Sta. Res. Note INT-305. 7 p.

CLEARY, B.D. and B.R. KELPSAS. 1981. Five steps to successful regeneration planning. Oreg. State Univ., For. Res. Lab., Corvallis, OR. Special Publ. 1. 31 p.

COATES, D. and S. HAEUSSLER. 1984. A guide to the use of mechanical site preparation equipment in North Central British Columbia. B.C. Min. For., Victoria, B.C. 54 p.

________ 1985. A preliminary guide to the response of major species of competing vegetation to silvicultural treatments. B.C. Min. For., Victoria, B.C. Land Manage. Handb. No. 9.

COCHRAN, P.H. and T. BROCK. 1985. Soil compaction and initial height growth of planted ponderosa pine. USDA For. Serv., Pac. NW For. Range Exp. Sta. Res. Note PNW-434. 4 p.

COLE, D.W., S.P. GESSEL, and S.F. DICE. 1967. Distribution and cycling of nitrogen, phosphorus, potassium and calcium in a second-growth Douglas fir ecosystem. *In* Proc. Symp. Primary Productivity and Mineral Cycling in Natural Ecosystems. Univ. Maine Press, Orono, ME. pp. 197-232.

COMEAU, P.G., M.A. COMEAU, and G.F. UTZIG. 1982. A guide to plant indicators of moisture for southeastern British Columbia, with engineering interpretations. B.C. Min. For., Nelson, B. C. Land Manage. Handb. No. 5. 119 p.

COOK, M.H. AND J.G. KING. 1983. Construction cost and erosion control effectiveness of filter windrows on fill slopes. USFS For. Serv., Intermount. For. Range Exp. Stn., Ogden, UT. Res. Note INT-335. 5 p.

COTTELL, P.L., B.A. MCMORLAND, and G.V. WELLBURN. 1976. Evaluation of cable logging systems in Interior B.C. and Alberta. FERIC, Vancouver, B.C. Tech. Rep. No. TR-8. 41 p.

CROMACK, K., JR., F.J. SWANSON and C.G. GRIER. 1979. A comparison of harvesting methods and their impact on soils and environment in the Pacific Northwest. *In* Forest soils and land use. Proc. 5th N. Am. For. Soils Conf. USDA For. Serv. pp. 449-475.

CURRAN, M. 1986. Short and long-term effects of slashburning on soil properties, tree growth and nutrition on some coastal B.C. sites. Univ. B.C., Dept. Soil Sci., Vancouver, B.C. Unpubl. paper presented at NW Fire Council Annual Meeting. 37 p.

DADDOW, R.L. and G.E. WARRINGTON. 1983a. Growth-limiting soil bulk densities as influenced by soil texture. USDA For. Serv., Watershed Systems Group. Fort. Collins, CO. 16 p.

________ 1983b. The influence of soil texture on growth-limiting soil bulk densities. *In* New forests for a changing world. Proc. 1983 SAF Nat. Conv., Portland, OR. pp. 252-256.

DEBYLE, N.V. 1976. Fire, logging, and debris disposal effects on soil and water in northern coniferous forests. IUFRO, Div. 1. Proc. 16th IUFRO World Congr., Oslo, Norway. pp.201-212.

________ 1981. Clearcutting and fire in the larch/Douglas-fir forest of Montana: a multifaceted research summary. USDA For. Serv. Gen. Tech. Rep. INT-99. 73 p.

DEBYLE, N.V. and P.E. PARKER. 1972. Plant nutrient and soil losses in overland flow from burned forest clearcuts. Nat. Symp. Watersheds in Transition. pp. 296-307.

DEKIMPE, C.R., M. BERNIER-CARDOU, and P. JOLICOEUR. 1981. Compaction and settling of Quebec soils in relation to their soil-water properties. Can. J. Soil Sci. 62:165-175.

DE VERA, M.R. 1981. Assessment of sediment yield using the universal soil loss equation. *In* Erosion and sediment in Pacific Rim Steeplands. I. A. H. S. Publ. No. 12: 400-414.

DE VRIES, J. 1983. Degradation effects of soil compaction. *In* Soil degradation in British Columbia. Proc. 8th B.C. Soil Sci. Workshop, B.C. Min. Agric. Food, Victoria, B.C. pp. 91-121.

DE VRIES, J. and T.L. CHOW. 1978. Hydrologic behavior of a forested mountain soil in coastal British Columbia. Water Resources Res. 14 (5): 935-942.

DICKERSON, B.P. 1976. Soil compaction after tree-length skidding in northern Mississippi. Soil Sci. Soc. Am. J. 40: 965-966.

DISSMEYER, G.E. and G.R. FOSTER. 1980. A guide for predicting sheet and rill erosion on forest land. USDA For. Serv. Tech. Publ. SA-TP 11. 40 p.

DOBBS, R.C. and R.G. McMINN. 1977. Effects of scalping on soil temperature and growth of white spruce seedlings. *In* Energy, water and the physical environment of the soil. Proc. 6th B.C. Soil Sci. Workshop, Richmond, B.C. pp. 66-73.

DONNELLY, D.M. 1977. Estimating the least cost combination of cable yarding and tractor skidding for a timber sale area. USDA For. Serv. Res. Note RM-341. 8 p.

________ 1978. Computing average skidding distance for logging areas with irregular boundaries and variable log density. USDA For. Serv., Rocky Mountain For. Range Exp. Sta. Gen. Tech. Rep. RM-58. 11 p.

DONNELLY, J.R. and J.B. SHANE. 1986. Forest ecosystem responses to artificially induced soil compaction. I. Soil physical properties and tree diameter growth. Can. J. For. Res. 16: 750-754.

DYCK, W.J. 1976. Site preparation for regeneration in the Nelson Forest District of British Columbia. M. F. thesis. Univ. B.C. Fac. For., Vancouver, B.C. 213 p.

DYRNESS, C.T. 1965. Soil surface condition following tractor and high-lead logging in the Oregon Cascades. J. For. 63: 272- 275.

________ 1967. Mass soil movement in the H. J. Andrews Experimental Forest. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland, OR. Res. Pap. PNW-42.

________ 1970. Stabilization of newly constructed road backslopes by mulch and grass-legume treatments. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland, OR. Res Note PNW- 123.

________ 1972. Soil surface conditions following balloon logging. USDA For. Serv., Pac. NW For. Range Exp. Sta. Res. Note PNW-182. 7 p.

________ 1976. Effect of wildfire on soil wettability in the high Cascades of Oregon. USDA For. Serv., Pac. NW For. Range Exp. Sta. Portland, OR. Res. Paper PNW-202. 18 p.

EMMINGHAM, W. 1982. Effects of compaction on seedling and tree growth. Oreg. State Univ., Dep. For. Sci., Corvallis, OR. Unpubl. Rep. 2 p.

ENTRY, J.A., N.M. STARK, and H. LOWENSTEIN. 1986. Effect of timber harvesting on microbial biomass fluxes in a northern Rocky Mountain forest soil. Can. J. For. Res. 16: 1076-1081.

EVEREST, F.H. 1978. Anadromous fish habitat and forest management: economic considerations. *In* Proc. 58th Ann. Cong. West. Assoc. Fish Wildl. Agencies and West Div. Am. Fish. Soc. pp. 153-171.

FELLER, M.C. 1982. The ecological effects of slashburning with particular reference to British Columbia: a literature review. B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 13. 60 p.

FINNIS, J.M., E.D. HETHERINGTON, R.V. QUENET, R.B. SMITH, and A.H. VYSE. 1973. Impacts of timber production practices on forest resource values in British Columbia. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Int. Rep. BC-47. 122 p. and appendices.

FISHER, R.F. 1984. Predicting tree and stand response to cultural practices. *In* Forest soils and treatment impacts. E. L. Stone (editor). Proc. 6th N. Am. For. Soils Conf. Dep. For., Wildl. Fisheries, Univ. Tennessee, Knoxville, TN. p. 52-65.

FLINT, A.L. AND S. CHILDS. 1983. Development and calibration of an irregular hole bulk density device. Soil Sci. Soc. Am. J. 48: 374-378.

FOREST ENGINEERING RESEARCH INSTITUTE OF CANADA. 1976. Handbook for ground skidding and road building in the Kootenay area of British Columbia. Vancouver, B.C. 41 p.

________ 1980. Site classification system promises reduced costs, efficient logging. Can. Pulp and Paper Industry, June 1980: 26-29.

FOREST RESEARCH INSTITUTE, ROTORUA. 1977. Improving the efficiency of ripping. For. Ind. Rev. 8(8): 28, 31-32.

FOSTER, G.R. and W.H. WISCHMEIER. 1973. Evaluating irregular slopes for soil loss prediction. ASAE Paper No. 73-227, 1973 Ann. Meeting, Univ. Kentucky, Lexington, KY.

FREDRICKSEN, R.L. 1965. Sediment after logging road construction in a small Oregon watershed. USDA For. Serv., Misc. Publ. 970, Paper No. 8.

________ 1970. Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds. USDA For. Serv., Pac. NW. For. Range Exp. Sta., Portland, OR. Res. Pap. PNW-104. 15 p.

FREDRICKSEN, R.L., D.G. MOORE, and L.A. NORRIS. 1975. The impact of timber harvest, fertilization, and herbicide treatments on streamwater quality in western Oregon and Washington. *In* Forest soils and forest land management. B. Bernier and C. H. Winget (editors). Proc. 4th N. Am. For. Soils Conf. Les Presses de l'universite Laval, QUE. pp. 283-314.

FROEHLICH, H.A. 1973. The impact of even-age forest management on physical properties of soils. *In* Even-age management. R. K. Hermann and D. P. Lavender (editors). Oreg. State Univ., School For., Corvallis, OR. pp. 199-220.

________ 1976. The influence of different thinning systems on damage to soil and trees. *In* Proc. 16th IUFRO World Congress, Div. 4, Oslo, Norway. pp. 33-44.

________ 1978a. Soil compaction from low ground-pressure, torsion-suspension logging vehicles on three forest soils. Oregon State Univ., For. Res. Lab., Corvallis, OR. Res. Pap. 36. 12 p.

________ 1978b. The influence of clearcutting and road building activities on landscape stability in western United States. *In* Forest soils and land use. Proc. 5th N. Am. For. Soils Conf. Col. State Univ., Dep. For. Wood Sci., Fort Collins, CO. pp. 165-174.

________ 1979a. Soil compaction from logging equipment: effects on growth of young ponderosa pine, J. Soil Water Conserv. 34: 276-278.

________ 1979b. The effect of soil compaction by logging on forest productivity. Rep. to BLM, Contract No. 53500- CT4-5(N). Oreg. State Univ., For. Engineer. Dep., Corvallis, OR. 45 p.

________ 1979c. Skid trails and competition reduce growth rate of residual western hemlock. *In* Rep. to BLM, Contract No. 53500-CT4-5(N). Oreg. State Univ., For. Engineer. Dep., Corvallis, OR. pp. 22-27.

———— 1984. Mechanical amelioration of adverse physical soil conditions in forestry. *In* Proc. Symp. on Site Productivity of Past Growing Plantations. IUFRO, Pretoria and Pietermaritzburg, RSA. pp. 507-521.

———— 1986. Soil compaction: implications for young-growth management. *In* Managing young forests in the Douglas-fir Region. pp. 49-63.

———— 1988. Causes and effects of soil degradation due to timber harvesting. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 3-12.

FROEHLICH, H.A. and E.R. BERGLUND. 1979. The effect of soil compaction during thinning on the growth of residual trees. *In* Rep. to BLM, Contract No. 535000-CT4-5(N). Oreg. State Univ., For. Engineer. Dep., Corvallis, OR. 19 p.

FROEHLICH, H.A. and D.H. McNABB. 1984. Minimizing soil compaction in Pacific Northwest forests. *In* Forest soils and treatment impacts. E. L. Stone (editor). Proc. 6th N. Am. For. Soils Conf. Univ. Tennessee, Knoxville, TN. pp.159-192.

FROEHLICH, H.A. and D.W.R. MILES. 1978. Winged subsoiler tills compacted forest soil. For. Ind. 2:42-43.

FROEHLICH, H.A., D.E. AULERICH, and R. CURTIS. 1981. Designing skid trail systems to reduce soil impacts from tractive logging machines. Oreg. State Univ., School For., Corvallis, OR. Res. Paper 44. 15 p.

FROEHLICH, H.A., J. AZEVEDO, P. CAFFERATA, and D. LYSNE. 1980. Predicting soil compaction on forested land. Oreg. State Univ., Dep. For. Engineer., Corvallis, OR. Unpubl. Proj. summary. 3 p.

FROEHLICH, H.A., D.W. MILES, and R.W. ROBBINS. 1985. Soil bulk density recovery on compacted skid trails in central Idaho. Soil Sci. Soc. Am. J. 49: 1015-1017.

———— 1986. Growth of young *Pinus ponderosa* and *Pinus contorta* on compacted soil in central Washington. For. Ecol. Manage. 15: 285-294.

FROEHLICH, H.A., D.W.R. MILES, R.W. ROBBINS, and J.K. LYONS. 1983. Monitoring recovery of compacted skidtrails in central Idaho. Unpubl. soil monitoring proj. rep. on Payette Nat. Forest and Boise Cascade Lands. Payette Nat. For. McCall, ID. 58 p.

GAIRNS, G.H. 1987. Logging contract survey. Industrial Forestry Service Ltd., Prince George, B.C. (Compiled annually.)

GARDNER, R.B. 1979. Some environmental and economic effects of alternative forest road designs. Trans. ASAE 22(1): 63-68.

———— 1980. Skyline logging productivity under alternative harvesting prescriptions and levels of utilization in larch-fir stands. USDA For. Serv. Intermount. For. Range Exp. Sta. Resource Paper INT-247. 35 p.

———— 1982. Estimating production rates and operating costs of timber harvesting equipment in the northern Rockies. USDA For. Serv., Intermount. For. Range Exp. Sta. Gen. Tech. Rep. INT-118. 29 p.

GARLAND, J.J. 1983. Designated skidtrails to minimize soil compaction. *In* Designated skidtrails to reduce soil compaction. BLM training session. Salem District, Salem, OR. 14 p.

GARRISON, G.A. and R.S. RUMMEL. 1951. First year effects of logging on ponderosa pine forest range lands of Oregon and Washington. J. For. 49: 707-713.

GENT, J.A. and R. BALLARD. 1985. Impact of intensive forest management practices on the bulk density of lower coastal plain and Piedmont soils. South. J. Appl. For. 9(1): 44-48.

GENT, J. A. and L. A. MORRIS. 1986. Soil compaction from harvesting and site preparation in the upper Gulf Coastal Plain. Soil Sci. Soc. Am. J. 50: 443-446.

GENT, J.A., R. BALLARD, and A.E. HASSAN. 1983. The impact of harvesting and site preparation on physical properties of Lower Coastal Plain soils. Soil Sci. Soc. Am. J. 47: 595-598.

GENT, J.A., R. BALLARD. A.E. HASSAN and D.K. CASSEL. 1984. Impact of harvesting and site preparation on physical properties of Piedmont forest soils. Soil Sci. Soc. Am. J. 48: 173-177.

GESSEL, S.P., D.W. COLE, and J. TURNER. 1973. Elemental cycling and even-age management. *In* Even-age management. R. K. Hermann and D. P. Lavender (editors). Oreg. State Univ., School For., Corvallis, OR. pp. 178-198.

GOLDING, D.L. and C.R. STANTON. 1972. Water storage in the forest floor of subalpine forests of Alberta. Can. J. For. Res. 2(1): 1-6.

GRAHAM, R.T., A.E. HARVEY, J.R. TANN, and M.F. JURGENSEN. 1987. Soil organic reserves and their importance to conifer performance in the northern Rocky Mountains. USDA For. Serv. Intermount. For. Range Exp. Sta., Moscow, ID. Unpubl. 2 p.

GRAY, D.H. and W.F. MEGAHAN. 1981. Forest vegetation removal and slope stability in the Idaho batholith. USDA For. Serv., Intermount. For. Range Exp. Sta., Moscow, ID. Res. Pap. INT-271. 23 p.

GREACEN, E.L. and R. SANDS. 1980. Compaction of forest soils, a review. Aust. J. Soil Res. 18: 163-189.

HAGER, H. and M. SIEGHARDT. 1984. [Damage to forest sites through soil compaction. I. Soil physical changes to soils of different textures.] Central. fur des Gesamt Forst. 101(2): 109-120. (English summary in Forestry Abstracts.)

HAINES, L.W., T.E. MAKI, and S.G. SANDERFORD. 1975. The effect of mechanical site preparation treatments on soil productivity and tree (*Pinus taeda* L. and *P. elliottii* Engelm. var. *elliottii*) growth. *In* Forest soils and forest land management. B. Bernier and C.H. Winget (editors). Proc. 4th N. Am. For. Soils Conf. Les Presses de l'unversite Laval, QUE. pp. 379-395.

HALVERSON, H.G. and R.P. ZISA. 1982. Measuring the response of conifer seedlings to soil compaction stress. USDA For. Serv., NE For. Range Exp. Sta. Res. Paper NE-509. 6 p.

HAMMOND, H.L. 1978. Skid road layout study, 1977, Nelson Forest District. B.C. Min. For., Nelson, B.C. Unpubl. Rep. 126 p.

________ 1982. Ground skidding handbook for the Nelson Forest Region. B.C. Min. For., Nelson, B.C. Unpubl. Rep. 47 p.

________ 1984a. Evaluation of logging soil disturbance and logging efficiency FL A20192 of Block 3 Springer Creek. B.C. Min. For., Nelson, B.C. Unpubl. Contract Rep. 23 p.

________ 1984b. Soil disturbance levels in ground skidded clearcuts in southeastern B.C. *In* Proc. 1983 SAF Nat. Conv., Portland, OR. pp. 228-232.

________ 1985. Technical evaluation of forest management practices in the Nass River Valley. Silva Ecosystem Consultants Ltd., Winlaw, B.C. 220 p.

________ 1988a. A practical forest resources planning system. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 315-319.

________ 1988b. Soil degradation: costs of rehabilitation versus costs of prevention. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 227- 237.

HARVEY, A.E., M.P. JURGENSEN, and M.J. LARSEN. 1979. Biological implications of increased harvest intensity on the maintenance and productivity of forest soils. *In* Symp. on The environmental consequences of timber harvesting in Rocky Mountain coniferous forests. USDA For. Serv., Missoula, MT. Gen. Tech. Rep. INT-90.

HARVEY, A.E., M.F. JURGENSEN, M.J. LARSEN, and J.A. SCHLIETER. 1986. Distribution of active ectomycorrhizal short roots in forest soils of the Inland Northwest: effects of site and disturbance. USDA For. Serv., Intermount. For. Range Exp. Sta. Res. Pap. INT-374. 8 p.

HARVEY. A.E., M.J. LARSEN, and M.P. JURGENSEN. 1979. Ecology of ectomycorrhizae in northern Rocky Mountain forests. *In* Symp. on The Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests. USDA For. Serv., Missoula, MT. Gen. Tech. Rep. INT-90.

HATCHELL, G.E. 1981. Site preparation and fertilizer increase pine growth on soils compacted in logging. South. J. Appl. For. 5(2): 79-83.

HATCHELL, G.E. and C.W. RALSTON. 1971. Natural recovery of surface soils disturbed in logging. Tree Planters' Notes 22 (2): 5-9.

HATCHELL, G.E., C.W. RALSTON and R.R. FOIL. 1970. Soil disturbance in logging. J. For. 68: 772-775.

HAUPT, H. F. 1960. Variation in areal disturbance produced by harvesting methods in ponderosa pine. J. For. 58: 634-639.

HAZARD, J.W. and J.M. GEIST. 1984. Sampling forest soil conditions to assess impacts of management activities. Forest Soils and Treatment Impacts Workshop-Workshop Notes. pp. 442-430.

HEDIN, I.B. 1978. Timber and slope characteristics influencing future harvesting in British Columbia. FERIC, Vancouver, B.C. Tech. Rep. TR-21.

——— 1980. Comparison of two logging systems in Interior British Columbia: central processing yard vs. conventional. FERIC, Vancouver, B.C. Tech. Rep. No. TR-45. 53 p.

HEIDMANN, L.J. and D.B. THORUD. 1975. Effect of bulk density on frost heaving of six soils in Arizona. USDA For. Serv., Rocky Mountain For. Range Exp. Sta., Fort Collins, CO. Res. Note RM- 293. 4 p.

HEILMAN, P. 1981. Root penetration of Douglas-fir seedlings into compacted soils. For. Sci. 47: 660-666.

HELMS, J.A. and C. HIPKIN. 1986. Effects of soil compaction on tree volume in a California ponderosa pine plantation. West. J. Appl. For. 1 (4): 121-124.

HELMS, J.A., C. HIPKIN, and E.B. ALEXANDER. 1986. Effects of soil compaction on height growth of a California ponderosa pine plantation. West. J. Appl. For. 1 (4): 104-108.

HELVEY, J.D., A.R. TIEDEMANN, and T.D. ANDERSON. 1985. Plant nutrient losses by soil erosion and mass movement after wildfire. J. Soil Water Conserv. 40: 168-173.

HENDERSON, G.S. and D.L. GOLDING. 1983. The effect of slash burning on the water repellency of forest soils at Vancouver, British Columbia. Can. J. For. Res. 13: 353-355.

HENSHALL, J.K. and D.J. CAMPBELL. 1983. The calibration of a high resolution gamma-ray transmission system for measuring soil bulk density and an assessment of its field performance. J. Soil Sci. 34: 453-463.

HERRING, L.J. and R.G. McMINN. 1980. Natural and advance regeneration of Engelmann spruce and subalpine fir compared 21 years after site treatment. For. Chron. 56: 55-57.

HETHERINGTON, E.D. 1976. Dennis Creek: a look at water quality following logging in the Okanagan basin. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-Z-147. 33 p.

HILDEBRAND, E.E. 1983. [The influence of soil compaction on soil functions on forest sites.] Fortwissen Schaftichs. Centralblatt 102 (2): 111-115. (English summary in Forestry Abstracts.)

HILDEBRAND, E.E. and M. WIEBEL. 1982. [The influence of vehicle movement on site quality as represented by soil physical measurements.] Allg. Forst. -u J. Ztg. 153 (1/2): 24-34.

HILLHOUSE, M.I. and D.F. POTTS. 1982. Duff reduction in site preparation. *In* Proc. Symp. Site Preparation and Fuels Management on Steep Terrain. D.M. Baumgartner (editor). Wash. State Univ., Pullman, WA. pp. 67-73.

HOLDORF, H. 1982. Effects of site preparation and fuel management practices on soil productivity. *In* Proc. Symp. Site Preparation and Fuels Management on Steep Terrain. D.M. Baumgartner (editor). Wash. State Univ., Pullman, WA. pp. 63-65.

HOLLIS C.A., R.F. FISHER, and W.L. PRITCHETT. 1978. Effects of some silvicultural practices on soil site properties in lower coastal plains. *In* Forest soils and land use. Proc. 5th N. Am. For. Soils Conf., Col. State Univ., Dep. Forest Wood Sci., Fort Collins, CO. pp 585-606.

HOMOKY, S.G.J. 1984. Case histories of hydroseed research test sites. B.C. Min. For., Victoria, B.C. Res. Rep. RR84003- HG. 97 p.

———— 1987. Case histories of hydroseeded research test sites: post-1982 period. B.C. Min. For. Lands, Victoria, B.C. Res. Rep. RR87008-HQ. 103 p.

HOWARD, R.F. and M.J. SINGER. 1981. Measuring forest soil bulk density using irregular hole, paraffin clod, and air permeability. For. Sci. 27(2): 316-322.

HOWARD, R.F., M.J. SINGER, and G.A FRANTY. 1981. Effects of soil properties, water content, and compactive effort on the compaction of selected California forest and range soils. Soil Sci. Am. J. 45: 231-236.

HOWES, D.E. 1987. A terrain evaluation method for predicting terrain susceptible to post-logging landslide activity. A case study from the southern Coast Mountains of British Columbia. B.C. Min. Environ. Parks, Victoria, B.C. Tech. Rep. 28. 38 p.

HOWES, D.E. and M. SONDHEIM. 1988. Quantitative definitions of stability classes as related to post-logging clearcut landslide occurrence. Part II. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 167-184.

HOWES, S.W. 1988. Consideration of soil productivity during forest management activities - the USDA Forest Service approach in the Pacific Northwest. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 185-190.

HOWES, S.W. and D. HUGHES. 1981. Forest soil horizons. USDA For. Serv., Pac. NW Region, Portland, OR. Unpubl. Rep. No. 7.

HOWES, S.W., J.W. HAZARD, and J. M. GEIST. 1983. Guidelines for sampling some physical conditions of surface soils. USDA For. Serv., Pac. NW Region, Range Watershed Manage., Portland, OR. R6-RMW-146-1983. 34 p.

HUNGERFORD, R.D. 1979. Microenvironmental response to harvesting and residue management. *In* Symp. on Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests. USDA For. Serv., Ogden, UT. Gen. Tech. Rep. INT-90. pp. 37-73.

INTERIOR FOREST HARVESTING COMMITTEE - TECHNICAL ADVISORY COMMITTEE. 1989. Interim harvesting guidelines for the interior of B.C. Mimeo. 5 p.

JAKOBSEN, B.F. 1983. Persistence of compaction effects in a forest Kraznozen. Aust. J. For. Res. 13: 305-308.

JAKOBSEN, B.F. and G.A. MOORE. 1981. Effects of two types of skidders and of a slash cover on soil compaction by logging of mountain ash. Austr. J. For. Res. 11 (3/4): 247-255.

JONES, C.A. 1983. Effect of soil texture on critical bulk densities for root growth. Soil Sci. Soc. Am. J. 47: 1208-1211.

JURGENSEN, M.F., A.E. HARVEY, and M.J. LARSEN. 1981. Effects of prescribed fire on soil nitrogen levels in a cutover Douglas- fir/western larch forest. USDA For. Serv., Intermount. For. Range Exp. Sta. Res. Paper INT-275. 6 p.

KELLOGG, L.D. 1981. Machines and techniques for skyline yarding of smallwood. Oreg. State Univ., For. Res. Lab., Corvallis, OR. Res. Bull. 36. 15 p.

KENG, J.C.W. and L.E. LOWE. 1983. Degradation effects of soil organic matter loss. *In* Soil degradation in British Columbia. Proc. 8th B.C. Soil Sci. Workshop, B.C. Min. Agric. Food, Victoria, B.C. pp. 84-90.

KING, A. L. 1979. Measuring soil compaction in mechanically thinned pine plantations. ASAE Pap. 79-1600. 8 p.

KING, T. and S. HAINES. 1979. Soil compaction absent in plantation thinning. USDA For. Serv. Res. Note SO-251. 4 p.

KLOCK, G.O. 1975. Impact of five postfire salvage logging systems on soils and vegetation. J. Soil Water Conserv. 30 (2): 78-81.

________ 1976. Estimating two indirect logging costs caused by accelerated erosion. USDA For. Serv., Pac. NW For. Range Exp. Sta. Gen. Tech. Rep. PNW-44. 8 p.

________ Some soil erosion effects on forest soil productivity. Am. Soc. Agron. and Soil Sci. Soc. Am. 6 p.

KNIGHT, H.A W. 1964. Some effects of slash-burning and clearcut logging on soil properties and initial tree growth. Ph.D. thesis. Univ. Wash., Seattle, WA. 191 p.

KOGER, J.L., E.C. BURT, and A.C. TROUSE. 1985. Multiple pass effects of skidder tires on soil compaction. Trans. ASAE 28 (1): 11-16.

KRAEMER, J.F. and R.K. HERMANN. 1979. Broadcast burning: 25- year effects on forest soils in the western flanks of the Cascade Mountains. For. Sci. 25(3): 427-439.

KRAG, R.K. 1980. A method to estimate risk of soil erosion to logging sites in the Kootenay area of B.C. FERIC, Vancouver, B.C. Tech. Rep. TR-21. 55 p.

KRAG, R.K. and S.R. WEBB. 1987. Cariboo Lake logging trials: a study of three harvesting systems on steep slopes in the Central Interior of British Columbia. FERIC, Vancouver, B.C. Tech. Rep. TR-76. 48 p.

KRAG, R.K., K. HIGGINBOTHAM, and R. ROTHWELL. 1986. Logging and soil disturbance in southeast British Columbia. Can. J. For. Res. 16: 1345-1354.

KRAG, R.K., E.A. SAUDER, and G.V. WELLBURN. 1986. A forest engineering analysis of landslides in logged areas on the Queen Charlotte Islands, British Columbia. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. 43. 138 p.

KUENNEN, L., G. EDSON, and T.V. TOLLE. 1979. Soil compaction due to timber harvest activities. USDA For. Serv., North. Region. Soil Air & Water Notes 79-3. 6 p.

LAING, L.E. and S.W. HOWES. 1988. Detrimental soil compaction resulting from a feller buncher and rubber-tired skidder timber harvest operation: a case study. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 191-195.

LAVENDER, D.P. and M. NEWTON. 1986. Forest regeneration and forest health. *In* Impacts de l'homme sur la foret. IUFRO Symp., Strasbourg. INRA, Paris. pp. 216-236.

LEAF, C. F. 1974. A model for predicting erosion and sediment yield from secondary forest road construction. USDA For. Serv. Res. Note RM-274. 4 p.

LEAF, C.F. and R.R. ALEXANDER. 1975. Simulating timber yields and hydrologic impacts resulting from timber harvest on subalpine watersheds. USDA For. Serv., Rocky Mountain For. Range Exp. Sta. Res. Paper RM-123. 21 p.

LEWIS, T. 1988. Guidelines for timber harvesting prescriptions for interior sites of various degradation sensitivities. Timber Harvesting Methods Committee, B.C. Min. For. Lands, Victoria, B.C. Unpubl. Rep. 65 p.

LOCKABY, B.G. and C.G. VIDRINE. 1984. Effects of logging equipment traffic on soil density and growth and survival of young loblolly pine. South. J. Appl. For. 8(2): 109-112.

LOUSIER, J.D. and G.W. STILL (EDITORS). 1988. Degradation of forested lands: forest soils at risk. Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. 331 p.

LULL, H.W. 1959. Soil compaction on forest and range lands. USDA For. Serv. Misc. Publ. 768. 33 p.

LYSNE, D. 1983. Using designated skid trails. B.C. Min. For. Unpubl. Rep. F. S. 189 (1) INF 83/5.

MACE, A. C. JR. 1970. Soil compaction due to tree length and full tree skidding with rubber tyred skidders. Minn. For. Res. Note 214. 4 p.

MACE, A.C., JR., T. WILLIAMS, and J.C. TAPPEINER II. 1971. Effect of winter harvesting methods on soil bulk density and infiltration rates. Minn. For. Res. Note 228. 4 p.

McCAMMON, B.P. and D. HUGHES. 1980. Fire rehab in the Bend municipal watershed. *In* Proc. ASCE Symp. Watershed Manage., Boise, ID., 21-23 July 1980. 1: 252-259.

McCLURKIN, D.C. and P.D. DUFFY. 1975. Evaluating the impact of forest site preparation on soil and water quality in the U.S. Gulf Coast Plain. *In* Forest soils and forest land management. B. Bernier and C.H. Winget (editors). Proc. 4th N. Am. For. Soils Conf. Les Presses de l'universite Laval, QUE. pp. 315-322.

McCOLL, J.G. 1983. Advances in forest soil analysis. *In*: Forest soils and treatment impacts. E. L. Stone (editor). Proc. 6th N. Am. For. Soils Conf., Knoxville, TN. pp. 313-333.

McDONALD, M.J. 1979. Development and evaluation of the critical site yarder. FERIC, Vancouver, B.C. Tech. Note No. TN- 31. 30 p.

________ 1981. Evaluation of the Finning swing hydraulic yarder. FERIC, Vancouver, B.C. Tech. Note No. TN-40. 28 p.

MCLEOD, A.J. 1982. Summary of course on: Managing the impacts of soil compaction on forest lands: Oregon State University. B.C. Min. For., Prince George, B.C. 198 p.

________ 1983. Technical paper describing problems and strategies associated with harvesting sensitive slopes in the Prince George Region. B.C. Min. For., Prince George, B.C. Unpubl. Rep. 34 p.

________ 1988a. A pilot study of soil compaction on skid trails and landings in the Prince George Forest Region. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 275-280.

________ 1988b. A procedure for quantifying the volume loss associated with degraded areas and transition zones in the Prince George Forest Region. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 287-289.

McLEOD, A.J. and W.W. CARR. 1986. Rehabilitation of degraded forest soils in the Prince George Forest Region. *In* Land rehabilitation: policy, planning systems and operation programs. 11th Annual Meeting, CLRA, Univ. B.C., Vancouver, B.C.

McLEOD, A.J. and E. HOFFMAN. 1988. A pilot study of the amount of soil disturbance on selected cutovers in the Prince George Forest Region. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 281-286.

McMINN, R.G. 1974. Effect of four site treatments on survival and growth of white spruce and lodgepole pine seedlings. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Bi-mon. Res. Notes 30(3): 19-20.

———— 1984a. Guidelines for mechanical site preparation. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Unpubl. Rep. 17 p.

———— 1984b. Mechanical site treatment prescriptions should be based on site specific knowledge. *In* Mechanization of silviculture: increasing quality and productivity. Proc. CPPA/CFS Seminar on Mechanization of Silviculture. Thunder Bay, ONT. pp. 21-24.

———— 1986. Some silvicultural implications of the soil component of forest ecosystems. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Unpubl. Rep. 15 p.

McMORLAND, B.A. 1977. Evaluation of Volvo BM 971 clam bunk skidder. FERIC, Vancouver, B.C. Tech. Rep. No. TR-16. 43 p.

———— 1978. The Skagit GT3 grapple yarder and the Igland-Jones Highland Trailer Alp. FERIC, Vancouver, B.C. Tech. Note No. TN-19. 11 p.

———— 1980a. Skidding with small crawler-tractors. FERIC, Vancouver, B.C. Tech. Rep. No. TR-37. 89 p.

———— 1980b. Non-shearing felling heads. FERIC, Vancouver, B.C. Tech. Note No. TN-34. 48 p.

———— 1984. Production and performance of mechanical felling equipment in Interior B.C.: Harricana circular saw. FERIC, Vancouver, B.C. Tech. Note TN-74. 11 p.

———— 1985. Production and performance of ground skidding equipment in Interior B.C.: FMC FT-180/ John Deere 550 system. FERIC, Vancouver, B.C. Tech. Note No. TN-82. 20 p.

———— 1986. Production and performance of mechanical felling equipment in Interior B.C.: Timbco feller-buncher with Rotosaw head. FERIC, Vancouver, B.C. Tech. Rep. No. TR-67. 22 p.

McNABB, D.H. 1985. Does nitrogen lost from broadcast burns affect productivity. Oreg. State Univ., Corvallis, OR. FIR Rep. 7(3): 12-14.

———— 1988. Interpreting the effects of broadcast burning on forest productivity. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 89-103.

McNABB, D.H. and R.G. CAMPBELL. 1985. Quantifying the impacts of forestry activities on soil productivity. *In* Foresters' future: leaders or followers? Proc. 1985 SAF Nat. Conv., Fort Collins, CO. pp. 116-120.

McNABB, D.H. and H.A. FROEHLICH. 1983. Conceptual model for predicting forest productivity losses from soil compaction. *In* New forests for a changing world. Proc. 1983 SAF Nat. Conv. Portland, OR. pp. 261-265.

MAKI, T.E., E.F. THOMPSON, and D.D. MASON. 1962. Variation and levels of some foliar constituents of loblolly pine in relation to quality of site. N. C. Agric. Exp. Sta. Res. Paper No. 1497. 16 p.

MARCHANT, C.J. and J. SHERLOCK. 1984. A guide to selection and propagation of some native woody species for land rehabilitation in British Columbia. B.C. Min. For., Victoria, B.C. Res. Rep. RR84007-HQ. 117 p.

MAXWELL, J.A. 1987. Silvicultural site preparation equipment productivity. B.C. Min. For. Lands, Silv. Br., Victoria, B.C. 40 pp. and appendices.

MEGAHAN, W.F. 1972. Logging erosion, sedimentation: are they dirty words? J. For. 70: 403-407.

———— 1974a. Erosion over time on severely disturbed granitic soils: a model. USDA For. Serv., Intermount. For. Range Exp. Sta. Res. Paper INT-156. 14 p.

———— 1974b. Subsurface flow interception by a logging road in mountains of central Idaho. *In* Watersheds in transition. Am. Water Res. Assoc. and Col. State Univ. pp. 350- 356.

MEGAHAN, W.F. 1976. Tables of geometry for low-standard roads for watershed management considerations, slope staking and end areas. USDA For. Serv. Gen. Tech. Rep. INT-32. 104 p.

———— 1977. Reducing erosional impacts of roads. *In* Guidelines for watershed management. FAO Conserv. Guide. United Nations FAO, Rome. pp. 237-261.

———— 1981. Effects of silvicultural practices on erosion and sedimentation in the interior West: a case for sediment budgeting. *In* Proc. Symp. Interior West Watershed Manage. Wash. State Univ. Coop. Ext. Serv., Pullman, WA. pp. 169-181.

———— 1983. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. Water Resources Res. 19(3): 811-819.

———— 1984. Snowmelt and logging influence on piezometric reinforcement and moisture effects on slope stability. Transportation Res. Rec. 965, Wash., D.C. 8 p.

———— 1986. Recent Studies on Erosion and its control on Forest Lands in the United States. *In* 18th IUFRO World Congress, Div. 1, Vol I. pp. 178-189.

———— 1988. Roads and forest site productivity. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 54-65.

MEGAHAN, W.F. and W.J. KIDD. 1972a. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. J. For. 70: 136-141.

———— 1972b. Effects of logging roads on sediment production rates in the Idaho batholith. USDA For. Serv., Intermount. For. Range Exp. Sta. Res. Paper INT-123. 14 p.

MEGAHAN W.F. and P.N. KING. 1985. Identification of critical areas on forest lands for control of nonpoint sources of pollution. Environ. Manage. 9(1): 7-18.

MEGAHAN,W.F., N.F. DAY, and T.M. BLISS. 1978. Landslide occurrence in the western and central Northern Rocky Mountain physiographic province in Idaho. *In* Forest soils and land use. C. T. Youngberg (editor). Col. State Univ. Press, Fort Collins, CO. pp. 116-139.

MERSEREAU, R.C. and C.T. DYRNESS. 1972. Accelerated mass wasting after logging and slash burning in western Oregon. J. Soil Water Conserv. 27(3): 112-114.

MILES, D.W.R. and H.A. FROEHLICH. 1988.Objectives and evaluation of forest tillage. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 204-215.

MILES, D.W.R., F.J. SWANSON, and C.T. YOUNGBERG. 1984. Effects of landslide erosion on subsequent Douglas-fir growth and stocking levels in the western Cascades, Oregon. Soil Sci. Soc. Am. J. 48: 667-671.

MILES, J.A., B.R. HARTSOUGH, P. AVANTI, and W.J. CHANCELLOR. 1981. A soil compaction study on the Blodgett Experimental Forest. *In* Forest regeneration. Proc. ASAE Symp. Engineering Systems for Forest Regeneration. St. Joseph, MN. pp. 72-81.

MINKO, G. 1975. Effects of soil physical properties, irrigation and fertilizer on *Pinus radiata* seedling development in the Benalla Nursery. For. Comm., Victoria, Australia. For. Tech. Paper 22: 19-24.

MINORE, D. 1986. Effects of site preparation on seedling growth: a preliminary comparison of broadcast burning and pile burning. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland OR. Res. Note PNW-RN-452. 12 p.

MINORE, D., C.E. SMITH, and R.F. WOODARD. 1969. Effects of high soil density on seedling root growth of seven northwestern tree species. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland, OR. Res. Note PNW-112. 6 p.

MITCHELL, W.K. 1982. The construction and rehabilitation of logging landings in the Cariboo Forest Region. B.C. Min. For., Williams Lake, B.C. Res. Brief No. 20. 33 p.

MITCHELL, W.R. 1984. Interpretations for timber and silvicultural management in the Kamloops Forest Region. *In* Proc. Soil Management Implications in the Kamloops Forest Region. B.C. Min. For., Kamloops, B.C. Unpubl. Rep. 43 p.

MITCHELL, M.L., A.E. HASSAN, C.B. DAVEY, and J.D. GREGORY. 1982. Loblolly pine growth in compacted greenhouse soils. Trans. ASAE (1982): 304-307, 312.

MOEHRING, D.M. and I.W. RAWLS. 1970. Detrimental effects of wet weather logging. J. For. 68: 166-167.

MOON, D.E. 1988. Approaches to predicting soil degradation. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 138-152.

MORRIS, L.A., W.L. PRITCHETT, and B.F. SWINDEL. 1983. Displacement of nutrients into windrows during site preparation of a flatwood forest. Soil Sci. Soc. Am. J. 47 (3): 591-594.

MORRIS, W.G. 1970. Effects of slash burning in over-mature stands of the Douglas-fir Region. For. Sci. 16: 258-270.

MROZ, G.D., M.F. JURGENSON, A.E. HARVEY, and M.J. LARSEN. 1980. Effects of fire on nitrogen in forest floor horizons. Soil Sci. Soc. Am. J. 44: 395-400.

MURDOCH, D. and T. JONES. 1984. Soil monitoring and economic analysis at Rail Thin Timber Sale. *In* Feller buncher analysis. Oakridge Ranger District, Willamette Nat. Forest.

NIEHOFF, J. 1984. Technical guide to determine potential soil damage by prescribed burning and wildfire. Unpubl. Rep.

NORTHRUP, M.L. and J.R. BOYLE. 1975. Soil bulk densities after thirty years under different management regimes. Soil Sci. Soc. Am. Proc. 39: 588-589.

NYLAND, R.D., A.L. LEAF, and D.H. BICKELHAUPT. 1979. Litter removal impairs growth of direct-seeded Norway spruce. For. Sci. 25: 244-246.

O’LOUGHLIN, C.L. 1972. An investigation of the stability of the steepland forest soils in the Coast Mountains, southwest B.C. Ph.D. thesis. Univ. B.C., Vancouver, B.C. 147 p.

O’LOUGHLIN, C.L. and A.J. PEARCE (EDITORS). 1984. Symposium on effects of forest land use on erosion and slope stability. IUFRO, East-West Cent., N. Z. For. Serv., and USDA For. Serv. 310 p.

O’LOUGHLIN, C.L. and R.R. ZIEMER. 1982. The importance of root strength and deterioration rates upon edaphic stability in steepland forests. *In* Carbon uptake and allocation in sub-alpine ecosystems. Proc. IUFRO Workshop, Oreg. State Univ., Corvallis, OR. pp. 70-78.

OLSEN, E.D. and J.C. SEIFERT. 1984. Machine performance and site disturbance in skidding on designated trails. J. For. 82: 366-369.

PACKER, P.E. 1967. Criteria for designing and locating roads to control sediment. For. Sci. 13(1): 2-18.

PACKER, P.E. and G.F. CHRISTENSEN. 1964. Guides for controlling sediment from secondary logging roads. USDA For. Serv., Intermount. For. Range Exp. Sta., Ogden, UT. and North. Region, Missoula, MT. 42 p.

PACKER, P.E. and B.D. WILLIAMS. 1976. Logging and prescribed burning effects on the hydrologic and soil stability behavior of larch/Douglas-fir forests in the northern Rocky Mountains. *In* Proc. Montana Tall Timbers Fire Ecology Conf., and Fire and Land Manage. Symp., No. 14. Tall Timbers Res. Sta., Tallahassee, FL. pp. 465-479.

PAETH, R.C., M.E. HARWARD, E. G. KNOX, and C.T. DYRNESS. 1971. Factors affecting mass movement of four soils in the western Cascades of Oregon. Soil Sci. Soc. Am. Proc. 35: 943-947.

PASCOE, F.N. and D.D. MYROLD. 1988. Soil compaction and biological activity: a brief review. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 320- 325.

PATRIC, J.H. 1980. Effects of wood products harvest on forest soil and water relations. J. Environ. Qual. 9 (1): 73-80.

PATRIC, J.H. and W.E. KIDD. 1981. Erosion caused by low-cost roads in the Eastern Forest. *In* Forest regeneration. Proc. ASAE Symp. Engineering Systems for Forest Regeneration. St. Joseph, MI. pp. 22-29.

PERRY, T.O. 1964. Soil compaction and loblolly pine growth. USDA For. Serv. Tree Planting Notes: 67-69.

PERRY, D.A. and J. NORGEN. 1983. Impacts of biomass harvest on soil and nutrient loss. *In* Generating electricity with wood and solid wastes in southern Oregon. Oreg. State Univ., For. Res. Lab., Corvallis. OR. Res. Bull. 40. pp. 56-68.

PERRY, D.A. and S.L. ROSE. 1980. Productivity of forest lands as affected by site preparation. Paper presented Calif. Conf. Forest Tree Nutrition and Soil Fertility, 19-20 May 1980, Redding, CA. Oreg. State Univ., Corvallis, OR. 51 p.

PETERS, P.A. 1978. Spacing of roads and landings to minimize timber harvest cost. Forest Sci. 24(2): 209-217.

PFISTER, R.D. 1969. Effect of roads on growth of western white pine plantations in northern Idaho. USDA For. Serv., Ogden, UT. Res. Paper INT-65. 8 p.

POMEROY, K.B. 1949. The germination and initial establishment of loblolly pine under various surface soil conditions. J. For. 47: 541-543.

POTTER, M.K. and K.M. LAMB. 1974. Root development of radiata pine in the gravel soils of Eyrewell Forest, Canterbury. N. Z. J. For. 19: 264-275.

POWELL, L.H. 1978. Production and performance studies of FMC 200 series skidders. FERIC, Vancouver, B.C. Tech. Rep. No. TR- 29. 37 p.

POWELL, L.H. and D.W. MYHRMAN. 1977. Evaluation of Earls ParaShear feller-buncher. FERIC, Vancouver, B.C. Tech. Rep. No. TR-17. 45 p.

POWELL, L.H. and G. ST. JEAN. 1979. Trial of OSA 670 feller buncher and OSA 705 processor in British Columbia. FERIC, Vancouver, B.C. Tech. Rep. No. TR-31. 58 p.

PYE, J.M. and P.M. VITOUSEK. 1985. Soil and nutrient removals by erosion and windrowing at a southeastern U. S. Piedmont site. For. Ecol. Manage. 11: 145-155.

RADTKE, S. and D. HUGHES. 1975. Field report on performance of FMC Model 200 CA. USDA For. Serv., Umpqua Nat. Forest, Oregon. 3 p.

RAGHAVAN, G.S.V., E. McKYES, and F. TAYLOR. 1981. Soil compaction effects on soil productivity. *In* Forest regeneration. Proc. ASAE Symp. Engineering Systems for Forest Regeneration. St. Joseph, MI. pp. 90-97.

RAWITZ, E., H. ETKIN, and A. HAZAN. 1982. Calibration and field testing of a two-probe gamma gauge. Soil Sci. Soc. Am. J. 46: 461-465.

REVEL, J. 1976. A review of windrowing practices in British Columbia. Comm. Mech. Silv. 26 p. and appendix.

RICE, R.M. and P.D. GRADEK. 1984. Limits on the usefulness of erosion-hazard ratings: experiences in northwestern California. Can. J. For. Res. 14: 559-564.

RICE, R.M., N.H. PILLSBURY, and K.W. SCHMIDT. 1985. A risk analysis approach for using discriminant functions to manage logging-related landslides on granitic terrain. For. Sci. 31: 772-784.

RITARI, A. 1977. Effect of site preparation on physical properties of the soil in a thick-humus spruce stand. M.Sc. thesis. Univ. B.C., Dep. Soil Sci., Vancouver, B.C. 60 p.

ROLLERSON, T.P. and C.A. KENNEDY. 1984. Compactive effects of a low ground pressure skidder. Woodlands Serv. Div., MacMillan Bloedel Ltd., Nanaimo, B.C. 43 p.

ROLLERSON, T.P., D.E. HOWES, and M.W. SONDHEIM. 1986. An approach to predicting post-logging slope stability for coastal B.C. Paper presented at NCASI West Coast Reg. Meeting., Portland, OR.

ROOD, K.M. 1984. An aerial photograph inventory of the frequency and yield of mass wasting on the Queen Charlotte Islands, British Columbia. B.C. Min. For., Land Manage. Rep. 34. 55 p.

ROSS, D.W. and J.D. WALSTAD. 1986. Effects of site preparation on ponderosa pine, associated vegetation, and soil properties in south central Oregon. Can. J. For. Res. 16: 612-618.

ROTHACHER, J.S. and T.B. GLAZERBROOK. 1968. Flood damage in the national forests of Region 6. USDA For. Serv., Pac. NW For. Range Exp. Sta., Portland, OR. 20 p.

ROTHWELL, R.L. 1971. Watershed management guidelines for logging and road construction. Can. For. Serv., North. For. Res. Cent., Edmonton, ALTA. Inf. Rep. A-X-42. 78 p.

_______ 1978. Watershed management guidelines for logging and road construction in Alberta. Can. For. Serv., North. For. Res. Cent., Edmonton, ALTA. Inf Rep. NOR-X-208. 43 p.

ROUTLEDGE, R.D. 1987. The impact of soil degradation on the expected present net worth of future timber harvests. For. Sci. 33(4): 823-834.

_______ 1988. Assessing long-term costs of forest soil degradation. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G. Still (editors). Proc. 10th B.C. Soil Sci. Workshop. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Report No. 56. pp. 223-226.

RUARK, G.A., D.L. MADEM, and T.A. TATTAT. 1982. The influence of soil compaction and aeration on the root growth and vigour of trees-a literature review-Part I. Arborcultural J. 6: 251-265.

RUAULT, R.E. 1982. Surface systems approach to handling small timber on critical sites. *In* The small tree resource: a materials handling challenge. For. Products Res. Soc., Madison, WI. Proc. 7306. pp. 129-135.

RUTH, R.H. 1967. Silvicultural effects of skyline crane and highlead yarding. J. For. 65: 251-255.

RYDER, J.M. 1983. Soil degradation by mass movement in British Columbia. *In* Soil degradation in British Columbia. Proc. 8th B.C. Soil Sci. Workshop. B.C. Min. Agric. Food, Victoria, B.C. pp. 192-213.

SANDS, R., E.L. GREACEN, and C.J. GERARD. 1979. Compaction of sandy soils in radiata pine forests. I: A penetrometer study. Austr. J. Soil Res. 17: 101-113.

SANTO, L.T. and G.Y. TSUJI. 1977. Soil bulk density and water content measurements by gamma-ray attenuation techniques. Hawaii Agric. Exp. Sta., Univ. Hawaii, Coll. Tropical Agric. Tech. Bull. 98: 1-16.

SCHOENBERGER, M.M. and D.A. PERRY. 1982. The effect of soil disturbance on growth and ectomycorrhizae of Douglas-fir and western hemlock seedlings: a greenhouse bioassay. Can. J. For. Res. 12: 343-353.

SCHROEDER, W.L. and D.N. SWANSTON. 1987. Application of geotechnical data to resource planning in southeast Alaska. USDA For. Serv., Pac. NW For. Range Exp. Sta. Gen. Tech. Rep. PNW- 198. 22 p.

SCHURMAN, B.J. and E.E. MacKINTOSH. 1985. Susceptibility of forest soils to compaction during logging operations in the northern region great clay belt. Univ. Guelph, Ont. Inst. Pedology, Dep. Land Resource Sci., 11 p. and appendix.

SCHWAB, J.W. 1976. Soil disturbance associated with steep slope logging in the Quesnel Highlands, Cariboo Forest District. Unpubl. B.Sc. thesis. Univ. B.C., Fac. For., Vancouver B.C. 54 p.

———— 1978. Soil disturbance associated with tractor skidding, access logging, and highlead yarding in the Prince Rupert Forest District. B.C. For. Serv., Prince Rupert, B.C. 12 p.

———— 1983. Mass wasting: October-November 1978 storm, Rennel Sound, Queen Charlotte Islands, British Columbia. B.C. Min. For., Victoria, B.C. Res. Note No. 91. 23 p.

———— 1988. Mass wasting impacts to forest land: forest management implications, Queen Charlotte Timber Supply Area. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 104-115.

SCHWAB, J.W. AND W.J. WATT. 1981. Logging and soil disturbance on steep slopes in the Quesnel Highlands, Cariboo Forest Region. B.C.For. Serv. Res. Note No. 88. 15 p.

SEIFERT, J.C.W. 1982. Production rates and residual stand impact for four skidding machines during overstory removal. Ph.D. thesis. Oreg. State Univ., Corvallis, OR. 127 p.

SESSIONS, J., J.C. BALCOM, and K. BOSTON. 1987. Road location and construction practices: effects on landslide frequency and size in the Oregon Coast Range. West. J. Appl. For. 2(4): 119- 124.

SIDLE, R.C. 1980a. Impacts of forest practices on surface erosion. USDA For. Serv., Oreg. State Univ. PNW-195. 15 p.

———— 1980b. Slope stability in forest land. USDA For. Serv., Pac. NW For. Range Exp. Sta. Ext. Publ. PNW-209. 23 p.

SIDLE, R.C. and D.M. DRLICA. 1981. Soil compaction from logging with a low-ground-pressure skidder in the Oregon Coast Ranges. Soil Sci. Soc. Am. J. 45: 1219-1224.

SIDLE, R.C., A.J. PEARCE, and C.L. O'LOUGHLIN. 1985. Hillslope stability and land use. Am. Geophys. Union. Water Resources Monogr. Series 11. 140 p.

SKINNER, M.F. and G.D. BOWEN. 1974. The penetration of soil by mycelial strands of ectomycorrhizal fungi. Soil Biol. Biochem. 6: 57-61.

SMITH, D.M. 1970. Concentrations of soil nutrients before and after fire. Can J. Soil Sci. 50: 17-29.

SMITH, R.A. 1988a. Environmental impact of ground harvesting systems on steep slopes in the Vernon Forest District. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 13-27.

———— 1988b. Harvesting guidelines for the Vernon Forest District: contour strip logging, skidroads and landings. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 266-274.

SMITH, R.B. 1975. Report on field workshops on windrowing, Nelson Forest District - Sept. 8-11, 1975; Kamloops Forest District - Sept. 15-19, 1975. Can. For. Serv., Victoria, B.C. Unpubl. Rep. 11 p.

———— 1984a. Soils and management implications in the Kamloops Forest Region. (5) Maintenance of site productivity. ABCPF. Continuing Education Course, Dec. 13-14, 1984, Kamloops, B.C. 12 p.

———— 1984b. Summary of site productivity. Outline of lecture presented at an ABCPF Continuing Education Course, Feb. 7-8, 1984 at Selkirk College, Castlegar, B.C. 14 p.

SMITH, R.B. and E.F. WASS. 1976. Soil disturbance, vegetative cover and regeneration on clearcuts in the Nelson Forest District, British Columbia. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-X-151. 37 p.

———— 1979. Tree growth on and adjacent to contour skidroads in the subalpine zone, southeastern British Columbia. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-R-2. 26 p.

——— 1980. Tree growth on skidroads on steep slopes logged after wildfires in central and southeastern British Columbia. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-R-6. 28 p.

——— 1983a. Changes in ground surface characteristics and vegetative cover associated with logging and prescribed broadcast burning. *In* Proc. Carnation Creek Workshop, a 10-year review. G. Hartman (editor). Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. pp. 100-109.

——— 1983b. Preliminary assessment of impacts of two stumping operations on site productivity, interior British Columbia. Proc. 1983 SAF Nat. Conv., Portland, OR. pp. 247-251.

——— 1985a. Changes in soil surface conditions at Marl Creek root-rot control site. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Unpubl. Rep. 11 p.

——— 1985b. Some chemical and physical characteristics of skidroads and adjacent undisturbed soils. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-X-261. 28 p.

SMITH, R.B., P.R. COMMANDEUR and M.W. RYAN. 1984. Vegetation succession, soil development and forest productivity on landslides, Queen Charlotte Islands, British Columbia, Canada. *In* Proc. IUFRO Symp. on Effects of Forest Land Use on Erosion and Slope Stability. C.L. O'Loughlin and A.J. Pearce (editors). Honolulu, HA. pp. 109-116.

——— 1986. Soils, vegetation, and forest growth on landslides and surrounding logged and old-growth areas on the Queen Charlotte Islands. B.C. Min. For., Victoria, B.C. Land. Manage. Rep. No. 41. 95 p.

STANDING SENATE COMMITTEE ON AGRICULTURE, FISHERIES AND FORESTRY. 1984. Soil at risk: Canada's eroding future. Committees and Private Legis. Br., The Senate of Canada, Ottawa, ONT. 129 p.

STANDISH, J.T. 1984. Soil disturbance from logging on steep slopes. Proj. 83-077. Talisman Land Resource Consultants. Vancouver, B.C.

STANDISH, J.T., P.R. COMMANDEUR, and R.B. SMITH. 1988. Impacts of forest harvesting on physical properties of soil with particular respect to increased biomass recovery: a review. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC- X-301. 24 p.

STARK, N.H. 1979. Nutrient losses from timber harvesting in a larch/Douglas-fir forest. USDA For. Serv., Intermount. For. Range Exp. Sta. Res. Paper INT-231. 41 p.

STATHERS, R.J. 1985. Soil climate: implications for forest management. Univ. B.C., Dep. Soil Sci., Vancouver, B.C. Unpubl. Rep. 8 p.

STEINBRENNER, E.C. 1955. The effect of repeated tractor trips on the physical properties of two forest soils in southwestern Washington. Northwest Sci. 29: 155-159.

STEINBRENNER, E.C. and S.P. GESSEL. 1955a. Effect of tractor logging on soils and regeneration in the Douglas-fir Region of southwestern Washington. SAF Proc. 1955: 77-80.

——— 1955b. The effect of tractor logging on physical properties of some forest soils in Southwestern Washington. Soil Sci. Soc. Am. Proc. 19: 372-376.

STEWART, R., H. FROEHLICH, and E. OLSEN. 1988. Soil compaction: an economic model. West. J. Appl. For. 3(1): 20-22.

STILL, G.W. 1988. Degradation of forested land - research needs. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 259-264.

STILL, G.W. and D. MACDONALD. 1987. Maintaining productive forest soils...our future depends on it. B.C. Min. For. Lands, Nelson and Victoria, B.C. Inf. brochure. 6 p.

STILL G. and S. THOMPSON. 1987. Evaluation of soil disturbance in the Golden Forest District. B.C. Min. For. Lands, Nelson, B.C. Unpubl. Working Plan, EP 1022. 12 p.

STRANSKY, J.J. 1981. Site preparation effects on soil bulk density and pine seedling growth. South. J. Appl. For. 5(4): 176-180.

SULLIVAN, J., P.N. OMI, A.A. DYER, and A. GONZALES-CABAN. 1987. Evaluating the economic efficiency of wildfire rehabilitation treatments. West. J. Appl. For. 2(2): 58-61.

SWANSON, F.J. and C.T. DYRNESS. 1975. Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology 3: 393-396.

SWANSTON, D.N. and F.J. SWANSON. 1976. Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest. *In* Geomorphology and engineering. D.R. Coates (editor). Dowden, Hutchinson & Ross, Inc. Stroudsburg, PA. pp. 199-221.

SWITZER, G.L., D.M. MOEHRING AND T.A. TERRY. 1978. Clearcutting vs. alternative timber harvesting-stand regeneration systems: effects on soils and environment of the South. *In* Forest soils and land use. Proc. 5th N. Am. For. Soils Conf., Col. State Univ., Dep. For. Wood Sci., Fort Collins, CO. pp. 477-515.

TACKLE, D. 1962. Infiltration in a western larch-Douglas-fir stand following cutting and slash treatment. USDA For. Serv., Intermount. For. Range Exp. Sta., Ogden, UT. Res. Note INT-89. 7 p.

TAYLOR, S.W. and M.C. FELLER. 1986. Initial effects of slashburning on the nutrient status of Sub-Boreal Spruce Zone ecosystems. Fire Manage. Symp., Prince George, B.C., April 8-9, 1986. 12 p.

TERRY, T.A. and R.G. CAMPBELL. 1981. Soil management considerations in intensive forest management. *In* Forest regeneration. Proc. ASAE Symp. Engineering Systems for Forest Regeneration. St. Joseph, MI. pp. 98-106.

TERRY, T.A. and J.H. HUGHES. 1975. The effects of intensive management on planted loblolly pine (*Pinus taeda* L.) growth on poorly drained soils of the Atlantic Coastal Plain. *In* Forest soils and forest land management. B. Bernier and C.H. Winget (editors). Proc. 4th N. Am. For. Soils Conf. Les Presses de l'universite Laval, QUE. pp. 351-378.

TERRY, T.A., D.K. CASSEL, and A.G. WOLLUM II. 1981. Effects of soil sample size and included root and wood on bulk density in forested soils. Soil Sci. Soc. Am. J. 45: 135-138.

THOMPSON, C.F. 1978. Drag scarification trials in lodgepole pine logging slash in the Nelson Forest District of British Columbia. B.C. Min. For., Victoria, B.C. Res. Note No. 82. 13 pp.

THOMPSON, S. 1988. Quantification of soil disturbance following logging in the Golden TSA. B.C. Min. For. Lands, Nelson, B.C. Unpubl. Rep.

THORUD, D.B. and S.S. FRISSEL, JR. 1976. Time changes in soil density following compaction under an oak forest. Minn. For. Res. Note 257. 4 p.

TIMBER MANAGEMENT RESEARCH. 1978. Uneven-aged silviculture and management in the United States. USDA For. Serv. Gen. Tech. Rep. WO-24. 234 p.

TROWBRIDGE, R., B. HAWKES, A. MACADAM, and J. PARMINTER. 1986. Field handbook for prescribed fire assessments in British Columbia: logging slash fuels. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Handb. No. 11. 63 p.

UTZIG, G.F. and L. HERRING. 1974. Factors significant to high elevation forest management. B.C. For. Serv. Rep. EP 735. 69 p.

________ 1975. Forest harvesting impacts at high elevations: five case studies. B.C. Min. For., Victoria, B.C. Res. Note No. 72. 85 p.

UTZIG, G.F. and M.E. WALMSLEY. 1988. Evaluation of soil degradation as a factor affecting forest productivity in British Columbia: a problem analysis. Phase I. Can. For. Serv., Pac. For. Cent., Victoria, B.C. FRDA Rep. 025. 111 p. and appendices.

VAN CLEVE, K. and C.T. DYRNESS. 1983. Effects of forest-floor disturbance on soil-solution nutrient composition in a black spruce ecosystem. Can. J. For. Res. 13: 894-902.

VAN DER WEERT, R. 1974. Influence of mechanical forest clearing on soil conditions and the resulting effects on root growth. Trop. Agric. 51(2): 325-331.

VIERECK, L.A., J. FOOTE, C.T. DYRNESS, K. VAN CLEVE, D. KANE, and R. SEIFERT. 1979. Preliminary results of experimental fires in the black spruce type of interior of Alaska. USDA For. Serv. Res. Note PNW-332. 27 p.

VIHNANEK, R.E. 1985. The effects of slashburning on the growth and nutrition of young Douglas-fir plantations in some dry salal-dominated ecosystems. M.Sc. thesis. Univ. B.C., Fac. For., Vancouver, B.C. 98 p.

WAELTI, H. 1976. Long reach skylines. *In* Proc. Skyline Logging Symp., Vancouver, B.C.

WALMSLEY, M.E., G.F. UTZIG, and G.W. STILL. 1988. Evaluation of soil degradation as a factor affecting forest productivity in British Columbia - a problem analysis. Phase II and III - research needs and policy evaluation. Can. For. Serv., Pac. For. Cent., Victoria, B.C. FRDA Rep. 038. 43 p. and appendix.

WARRINGTON, G.E. 1978. Estimating soil erosion for forest land management planning: a procedure. *In* Forest soils and land use. C.T. Youngberg (editor). Proc. 5th N. Am. For. Soils. Conf., Col. State Univ., Dep. For. Wood Sci, Fort Collins, CO. pp. 174- 197.

WASTERLUND, I. 1985. Compaction of till soils and growth tests with Norway spruce and Scots pine. For. Ecol. Manage. 11: 171- 189.

WATT, W.J. and R.K. KRAG. 1988. A comparison of cable and small tractor logging soil disturbance. *In* Degradation of forested lands: forest soils at risk. J.D. Lousier and G.W. Still (editors). Proc. 10th B.C. Soil Sci. Workshop, B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. No. 56. pp. 44-53.

WEETMAN, G.F. 1983. Forestry practices and stress on Canadian forest land. *In* Stress on land. Lands Directorate, Ottawa, ONT. pp. 260-301.

WEETMAN, G.F. and B. WEBBER. 1972. The influence of wood harvesting on the nutrient status of two spruce stands. Can. J. For. Res. 2: 351-369.

WELLBURN, G.V. 1975. Alternative methods for logging steep slopes in the Nelson Forest District of British Columbia. Environ. Can., For. Manage. Inst., Ottawa, ONT. Inf. Rep. FMR-4- 76.

WELLS, C.G., R.E. CAMPBELL, L.F. DeBANO, C.E. LEWIS, R.L. FREDRIKSEN, E.C. FRANKLIN, R.C. FROEHLICH, and P.H. DUNN. 1979. Effects of fire on soil, a state-of-knowledge review. USDA For. Serv. Gen. Tech. Rep. WO-7. 34 p.

WERT, S. and B.R. THOMAS. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Sci. Soc. Am. J. 45: 629-632.

WHITE, W.A. 1988. A method for assessing the economic impacts of soil disturbance. Can. For. Serv., Pac. For. Cent., Victoria, B.C. Unpubl. Economics Rep. 23 p.

WOOLDRIDGE, D.D. 1960. Watershed disturbance from tractor and skyline crane logging. J. For. 53: 369-372.

WU, T.H. and D.N. SWANSTON. 1980. Risk of landslides in shallow soils and its relation to clearcutting in southeastern Alaska. For. Sci. 26 (3): 495-510.

YOUNGBERG, C.T. 1959. The influence of soil conditions following tractor logging on the growth of planted Douglas-fir seedlings. Soil Sci. Soc. Am. Proc. 23: 76-78.

ZIEMER, R.R. 1981. Roots and the stability of forested slopes. *In* Proc. Symp. Erosion and Sediment Transport in Pacific Rim Steeplands. T.R.H. Davies and A.J. Pearce (editors). Jan. 1981, Christchurch, New Zealand. Internat. Assoc. Hydrol. Sci. Publ. 132.

ZIEMER, R.R. and D.N. SWANSTON. 1977. Root strength changes after logging in southeastern Alaska. USDA For. Serv. Res. Note PNW-306. 10 p.

ZIEMKIEWICZ, P.F., S.K. TAKYI, and H. REGIER (EDITORS). 1980. Proc. Workshop on Reconstruction of Forest Soils in Reclamation. Reclam. Res. TAC, Alberta Land Conserv. Reclam. Coun. 160 p.