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J.T. Standish, P.R. Commandeur and R.B. Smith

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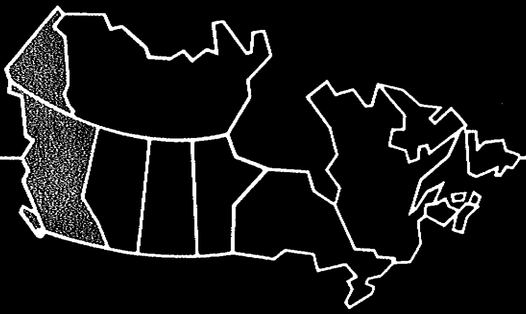

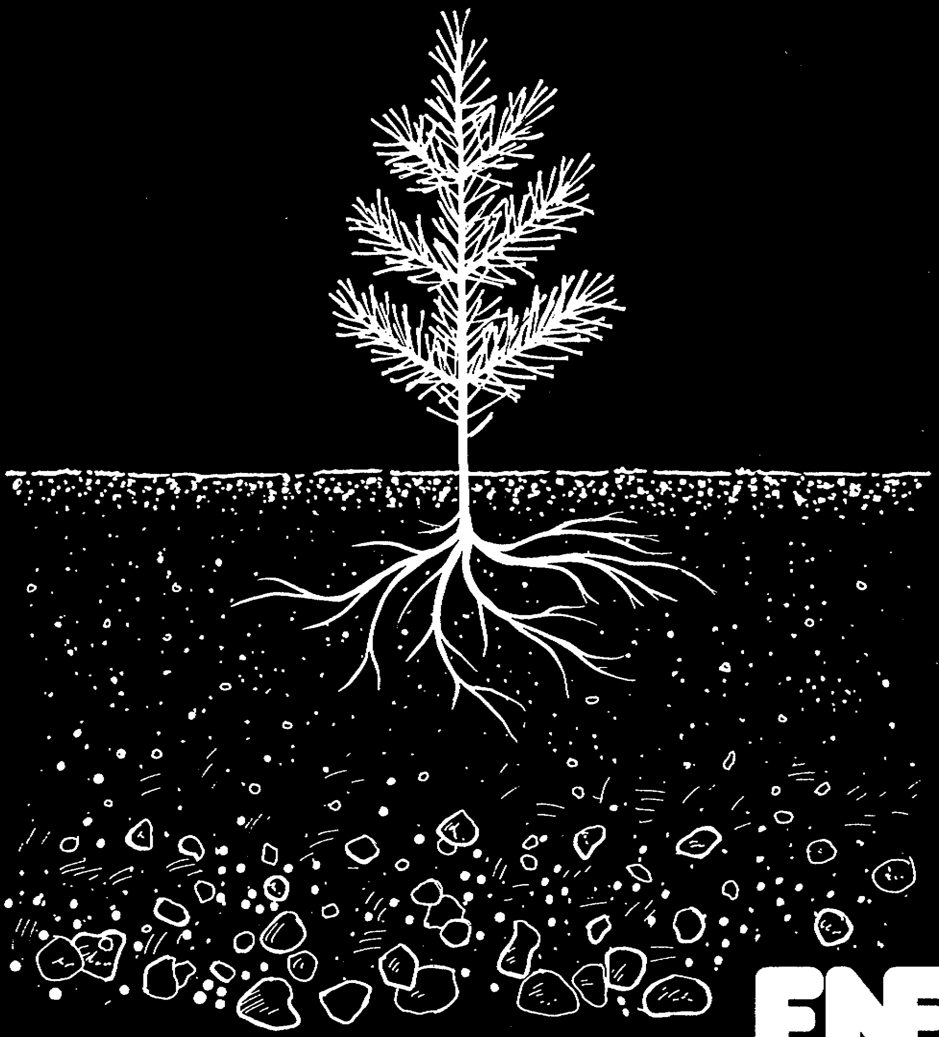

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Impacts of forest harvesting on physical properties of soils with reference to increased biomass recovery - a review

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Foreword

ENFOR is the acronym for the ENergy from the FORest (ENergie de la FORêt) program of the Canadian Forestry Service. This program of research and development is aimed at securing the knowledge and technical competence to facilitate in the medium to long term a greatly increased contribution from forest biomass to our nation's primary energy production. It is part of the federal government's efforts to promote the development and use of renewable energy as a means of reducing dependence on petroleum and other non-renewable energy sources.

The ENFOR program is concerned with the assessment and production of forest biomass with potential for energy conversion and deals with such forest-oriented subjects as inventory, harvesting technology, silviculture, and environmental impacts. (Biomass Conversion, dealing with the technology of converting biomass to energy or fuels, is the responsibility of the Renewable Energy Division of the Department of Energy, Mines and Resources). Most ENFOR projects, although developed by CFS scientists in the light of program objectives, are carried out under contract by forestry consultants and research specialists. Contractors are selected in accordance with science procurement tendering procedures of the Department of Supply and Services. For further information on the ENFOR Biomass Production program, contact ...

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Abstract

Research on impacts of forest harvesting on soils has shown that some operations are causing significantly reduced productivity for future crops. Additional stress on soils that may result from increasing wood recovery beyond the “close utilization” level is thus a matter for serious concern. The nature of operations directed toward increased wood recovery from cutovers is reviewed briefly. Literature dealing with physical soil impacts of forest harvesting and the subsequent effects on tree growth, particularly material published since 1970, is summarized, and the relevance of research results to increased biomass harvesting in British Columbia assessed. Additional wood recovery would involve mainly stemwood. Such recovery would be achieved primarily by conventional systems. Any increased physical soil impacts will likely result from an increase in traffic on existing roads and trails or a requirement for extra roads and trails to enable yarding of relatively small logs. As indicated by studies on stump extraction operations aimed at root-disease control, recovery of stumps and root systems would result in considerable additional soil disruption and a requirement for some nonconventional logging techniques.

Résumé

Les recherches réalisées sur les effets des méthodes d’exploitation forestière sur les sols ont démontré que certaines méthodes provoquent une baisse significative de productivité des récoltes suivantes. Le stress supplémentaire imposé au sol si l’on pousse le taux de recrû au-delà du seuil “d’utilisation intensive” devient alors un sujet inquiétant. L’auteur passe brièvement en revue les opérations destintes à accroitre le recrû sur les coupes rases. Il récapitule la bibliographie, surtout à partir de 1970, traitant des incidences physiques des méthodes d’exploitation sur le sol et sur la cruissance subséquente des arbres, et évalue la pertinence des résultats pour l’accroissement de la production de biomasse en Colombie-Britannique. Le recrû forestier supplèmentaire consisterait surtout en bois de fût et serait obtenu essentiellement par les mtthodes classiques. Les effets physiques éventuels sur le sol seraient liés à l’intensification de la circulation sur les routes et chemins forestiers ou à la construction de nouveaux chemins pour le débusquage de billes relativement petites. Comme le montrent les études sur les operations de dessouchage destinées & combattre les maladies racinaires, le dessouchage systématique augmenterait le dérangement du sol et exigerait l’utilisation de techniques d’exploitation forestière non conventionnelles.

Contents

Introduction

Several studies have examined the problems of increasing biomass recovery from forests in British Columbia (Blakeney 1980; Sinclair 1984, 1985). The impacts of such intensified harvest on various environmental areas have been addressed in general (Le Groupe Dryade 1980). An important aspect is the impact of intensified harvesting on physical properties of forest soils. This subject was dealt with in an annotated bibliography of literature on impacts of forest harvesting on the environment and resources (Bell et al. 1974, 1976) and in a review of the literature and evaluation of research needs (Bell et al. 1975) along with effects on a wide range of other ecosystem components. This report is an update of Bell's publications specifically in the area of soil physical properties. The objective of this report is to review the impact of timber harvesting on physical properties of forest soils and subsequent effects on tree growth with reference to the most likely biomass harvesting scenarios expected in British Columbia.

Biomass harvesting

Traditional harvesting of timber in British Columbia has meant the harvesting of stemwood only. Species and utilization standards have varied in response to changing markets, government policy, and technological conditions, but, by and large, stemwood has been the main timber resource. Other components of the tree such as branches, foliage, and root systems have not been utilized.

The upsurge of concern for the environment, the increasing demands for wood fibre for wood and pulp products and more recently for energy, the fact that stemwood and bark are known to account for only about 50% of the total dry matter production in coniferous crops (Young 1976; Keays and Hatton 1976), the availability of mechanized harvesting equipment, and the escalating costs of harvesting and transport have created a new set of circumstances. Interest in recent years has turned to the possibility of increasing wood recovery from our forest through increased biomass recovery (biomass harvesting). There may be other advantages of biomass harvesting: the elimination of the need to dispose of slash and therefore avoidance of associated costs and adverse impacts of piling and burning or broadcast burning (Feller 1982); improved accessibility for planting; removal of small, unstable debris from stream channels; and, in special cases, reduction in pest incidence,

As a working definition in this paper, biomass harvesting means the harvesting and recovery of wood fibre to any degree above and beyond the level defined as close utilization in British Columbia (British Columbia Ministry of Forests 1976). "Biomass harvesting" includes "whole-tree" and "full tree" utilization concepts where, to varying degrees, more than the conventional volume of stemwood is harvested. It is useful to think of biomass harvesting as occurring along a spectrum, with whole-tree utilization at one end and close utilization at the other.

Whole-tree utilization involves the harvesting of root systems, stumps, foliage and branches in addition to stemwood. It is technologically possible but currently considered uneconomic. There are, however, certain applications of whole-tree harvesting which have silvicultural rather than utilization objectives. For example, in some instances Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stumps are being operationally extracted after logging as a site preparation technique in order to reduce potential infection by root disease pathogens in new plantations (Wallis 1976; Morrison 1981). Stumps and root systems may also be extracted before felling by pushing the whole tree over (Weir and Johnson 1470). In a recent trial of this nature (B. Salmon, Evans Products, Golden, B.C., personal communication.) whole trees including root systems were ground skidded to the landing. Such a concentration of stumps at roadsides would allow more economical utilization than in normal stump extraction operations in which stumps are dispersed throughout the clearcut.

Full-tree utilization involves the utilization of the entire above-ground portions of a tree. This level of utilization is currently considered uneconomic. However, a higher degree of stemwood recovery beyond the level of utilization now in place and increased bark utilization as a source of hog fuel are within the realm of economic feasibility.

The most likely scenario for a "biomass" harvesting operation is a standard of recovery greater than the close utilization practices now in place. Biomass harvesting may involve only utilization of wood yarded to the road during normal yarding procedures (Sinclair 1985). This process would have little additional impact on soils. Or, biomass harvesting may involve utilization of wood dispersed throughout the clearcut. This would involve modifications to the primary yarding system. More turns may be required along the same cable yarding trails or additional tractor passes on the same skidroads. It may also require additional skid trails to enable yarding of short pieces. Second-pass logging could entail smaller, more adaptable equipment or even a change from cable to ground skidding (Rlakeney 1980). Our definition of biomass harvesting still allows a considerable range in the actual level of utilization likely to be attained in British Columbia. No attempt is made to define a particular level here.

Even if the possibility of biomass harvesting is remote at this time it is still of importance for long-term government planning, especially with regard to future potential energy supplies, and the possibility of providing part of this energy supply from forest residues. Technological advances, both in harvesting and processing, and relative changes in stumpage prices could create favorable economic conditions for biomass harvesting.

Given this framework, a knowledge of the impacts of conventional harvesting on soil physical properties becomes very relevant and useful. The implication is that €or a biomass harvesting operation, the degree of alteration of soil properties would most likely be more severe, distributed over a larger area, and have a greater impact on the productivity of a site than standard operations. To what extent this increased activity would affect productivity is largely unknown.

Impacts of timber harvesting on soil physical properties

Operation of logging machinery alters a number of physical soil properties including structure, porosity, density, pore size distribution, aeration, water retention, infiltrability, and hydraulic conductivity. The degree of alteration depends on soil strength, moisture content, and condition (frozen or unfrozen, snow cover or bare), the forces exerted on the soil by both equipment and logs and the frequency that logs and equipment pass over the soil. Productivity of subsequent crops can be adversely affected by harvesting impacts.

Harvesting can also be beneficial to forest soils. Effects such as improved soil thermal regimes associated with moist, exposed mineral soil, as well as control of competing vegetation, are examples. However, most research has documented adverse impacts such as increased rates of erosion, stream siltation, and degradation resulting from reduced “physical fertility” (Hillel 1980). This research supports the general consensus that soil degradation associated with conventional forest harvesting is a major problem in British Columbia (Ballard 1983a; Carr 1983; de Vries 1983; Young 1983; Standing Senate Committee on Agriculture, Fisheries and Forestry 1984; Agricultural Institute of Canada 1985).

Soil disturbance

Soil disturbance is defined here as any abrupt change in the physical, chemical, or biological properties of a soil. It is an inevitable consequence of timber harvesting. The magnitude of disturbance varies greatly depending on the logging method used, the type of terrain and soil, and the time of year that logging occurs. Helicopter or skyline systems produce the least soil disturbance since logs are suspended above ground for most of the distance from stump to landing. High lead logging, typical of coastal British Columbia logging operations, produces more disturbance, but the greatest amount of soil disturbance comes from ground skidding, typical of operations in the interior of the province. Ground skidding is becoming more prevalent on gentle terrain in coastal areas as second-growth stands of timber reach merchantable age.

The amount of exposed mineral soil has been regarded as a useful index of soil disturbance caused by forestry operations. Numerous disturbance surveys have been reported from British Columbia (Bockheim et al. 1975; Wilford 1975; Schwab 1976; Smith and Wass 1976; Schwab 1978; Schwab and Watt 1981; Standish 1984; Krag et al. 1986). Reported values of exposed mineral soil (excluding haulroads and landings) range from as low as 5%, for some helicopter or skyline yarded areas, to as high as 70% for some tractor-yarded areas. Hammond (1983) found that soil disturbance from ground skidding in the Nelson Forest Region ranged from 10 to 47% depending significantly on slope gradients. Studies have shown that logging on ample snow cover (e.g., more than 1 m) reduced soil disturbance by 50% when compared to sites without this protection (Smith and Wass 1976; Hammond 1983). Cable yarding does not always ensure a low percentage of exposed mineral soil. Bockheim et al. (1975) reported 56% exposed mineral soil for one extremely disturbed, high lead yarded area. The harvest of additional biomass from clearcut areas would likely result in a greater percentage of exposed mineral soil than that resulting from conventional harvesting practices. In the event that biomass harvesting would only involve roadside material, little additional impact would occur. However, biomass harvesting of wood dispersed throughout the clearcut could result in a significant increase in exposed mineral soil.

Mineral soil exposure has been used as an index of the potential for accelerated erosion and for degradation associated with reduced fertility. To make such inferences, knowledge of the extent, continuity, and severity of disturbance is usually necessary. Most disturbance surveys address the problem of severity by recording disturbance as either gouging or deposition to some arbitrary depth; for example, very deep disturbance has been defined as gouging to a depth greater than 25 cm (Smith and Wass 1976). The relationship between soil disturbance and tree establishment or growth is complicated by many interrelated factors (McColl 1983) and, except in extreme cases, considerable subjective judgement is required to infer degradation (Ballard 1983a). The subject is considered in more detail in a later section dealing with effects on tree growth.

Soil compaction

Soil compaction occurs when a soil is subjected to a pressure that exceeds its strength. The result is compression of the soil due to the rearrangement of soil particles and a decrease in pore volume. Compaction implies unsaturated conditions (Hillel €980). Most forest soils have air-filled macropores at water contents near field capacity (Froehlich and McNabb 1984). Therefore, true saturation rarely occurs, and compaction is generally always possible given a large enough compactive force. If a soil is wet enough, puddling can occur. Puddling results from the mechanical destruction of soil structure and the reorientation of soil particles with little or no change in overall soil volume (Braumack and Dexter 1978; Hillel 1980; de Vries 1983). Compaction and puddling can occur simultaneously and their effects can be difficult to separate (Froehlich and McNabb 1984). Forestry activities that result in soil compaction may also cause other alterations such as soil disturbance, soil displacement and exposure of denser subsoil (Dyrness 1965).

General discussions of compaction theory are given by Terzaghi and Peck (1967), Hillel (1980) and Das (1985). A general, thorough discussion (emphasizing agriculture) of compaction and its significance in British Columbia is given by de Vries (1983). A recent review of soil compaction and its significance to forestry with emphasis on the Pacific Northwest of the United States is presented by Froehlich and McNabb (1984).

From an engineering viewpoint, soil compaction is an intentional practice that increases the strength and decreases the permeability of unconsolidated material used for building roadbeds, earth dams, and other structures. In agriculture and forestry, compaction is usually considered a practice to be minimized or avoided (Hillel 1980). Soil properties that are directly affected by a decrease in pore volume due to compaction include: soil aeration, porosity and pore size distribution; soil water movement, infiltration capacity, hydraulic conductivity and water storage capacity; heat capacity, thermal conductivity and thermal diffusivity; and soil strength and compressibility.

Compaction indirectly affects tree growth. De Vries (1983) pointed out three deleterious effects of soil compaction:

a. Saturated hydraulic conductivity and infiltrability are reduced so that surface runoff and soil erosion are promoted.

b. Plant root growth and proliferation can be impaired from reduced soil aeration and increased mechanical impedance. Compacted surface layers can also interfere with seedling emergence.

c. Compaction causes increased cloddiness of fine textured surface soils and can result in soil-seed contact problems.

Cloddiness of surface soils is more commonly a problem with agricultural soils; however, it might be applicable to forestry, for example, in some areas that have been mechanically treated to enhance natural regeneration or improve plantability.

Bulk density, the mass of dry soil per unit volume of solid, liquid, and gaseous phases, is a commonly used measure of soil compaction. It is determined by numerous physical factors, such as particle size distribution, gradation, particle roughness, organic matter content, mineralogy of the clay fraction, and structure (Bodman and Constantin 1965; Lee and Suedkamp 1972; Alymore and Sills 1978; Cruse et al. 1980; DeKimpe et al. 1981; Howard et al. 1981 cited by Froehlich and McNabb 1984) and can be viewed as the net result of various biological and physical factors and forces that tend *to* consolidate or loosen the soil (Froehlich and McNabb 1984). Although bulk density provides a common measure of compaction, it does not indicate a soil's potential for compaction (Barley and Greacen 1967). The potential for compaction depends on soil strength, soil water content, organic matter content, and soil texture, as well as other factors, such as machine pressure exerted on the soil (Froehlich and McNabb 1984).

Studies by Steinbrenner and Gessel (1955), Dyrness (1965), Mace (1970), Dickerson (1976), and Kuennen et al. (1979) found that soil bulk density increased following harvesting. Mace (1970) showed that the increase in bulk density from tree-length skidding (tops and branches lopped off at stump) was about half of that from full-tree skidding (not lopped). Froehlich (1979) found that soil compaction on skid trails was in the order of 10% greater than that of adjacent, undisturbed soils. Lockaby and Vidrine (1984) found that soil bulk density was 12% higher on decks and primary roads compared with undisturbed areas. Gent and Ballard (1985) reported that traffic during harvesting significantly increased the soil bulk density to depths of 3 to 6 inches (7-15 cm) in areas outside primary skid trails and 9 to 12 inches (22-30 cm) on primary skid trails. In contrast, King (1979) and King and Haines (1979) found no significant increases in soil bulk density following thinnings in southern pine plantations. Smith and Wass (1985) found that the bulk density of gouged skidroad surfaces constructed on sloping ground averaged 59% higher than adjacent undisturbed mineral soil. At least some of the increased density on these skidroads resulted from soil displacement and exposure of naturally denser subsoil. They also showed that tracks on the outer (deposition) portion of skidroads were 35% denser and berms 22% denser on average than undisturbed mineral soil.

Most compaction occurs during the first few passes of a vehicle. Subsequent passes have less effect (Hatchell et al. 1970; Adams and Froehlich 1981) but may serve to increase density levels and reduce non-capillary porosity to critical levels for tree growth (Sidle and Drlica 1981; Burger et al. 1985). Where biomass harvesting would require an increase in the number of passes over conventional harvesting, soil compaction would be more severe. Moehring and Rawls (1970) found that more severe compaction occurs from traffic on saturated soils than on dry soils. Steinbrenner (1955) found that one trip with a tractor on a wet soil caused as much compaction as four trips on a dry soil.

Some forest soils having low bulk density and a high rate of infiltration often also have relatively low soil strength, making them easy to compact, displace, or mix during a timber harvesting operation. Other soils, for example some Gray Luvisols, have naturally high bulk densities; soil strength may be relatively high, at least when dry, but even slight compaction could significantly increase resistance to root penetration, and decrease infiltrability and aeration. The productivity of these soils may be impaired, resulting in a decrease in the growth rate. Biomass harvesting would probably aggravate this effect.

In theory, the potential. for compaction could be indicated by a soil's compression index, determined by applying a static load in a uniaxial consolidation test of unsaturated soils (Terzaghi and Peck 1967; Greacen and Sands 1980; Larson et al. 1980). In the field, complications such as variations in soil wetness (Larson et al. 1980), load duration (Dexter and Tanner 1974), and the nature of the applied stress (Soehne 1958; Froehlich and McNabb 1984) produce more compaction than would be predicted based on a static load (Cruse et al. 1980). Differences in soil horizons, occurrence of roots or large rocks, vegetation, and types of machinery also make compaction predictions difficult (Froehlich and McNabb 1984).

In engineering practice, a soil's maximum dry density is determined by means of a Proctor compaction test or a modification of the Proctor test (Proctor 1933; Terzaghi and Peck 1967; Hillel 1980; Das 1985). The result of the test is a moisture-density curve which indicates a maximum dry density at an optimum water content for a given compactive effort. Howard et al. (1981) used this approach to rank the susceptibility of soils to compaction. They found that approximately half of the forest and range soils they examined would remain at the optimum water content required for maximum compaction in the field for long periods of time. According to Froehlich and McNabb (1984), this approach does not give consistently reliable results because there is a tendency to overestimate compaction and to underestimate the optimum soil water content.

Soil strength tends to increase with increasing bulk density but the relationship is not simple (Barley and Greacen 1967). For example, for soils with similar particle size distributions, rough particles interlock and resist movement to a greater degree than do smooth particles (Cruse et al. 1980). Soil strength is also affected by soil water content: dry soils have greater strength than wet soils. Taylor and Bruce (1968) found that for some medium to coarse textured soils, penetrometer resistance (an indirect measure of soil strength) increased as the soil water potential decreased from -20 to -67 J/kg, even though bulk density did not change. Others finding similar trends include Paul and de Vries (1979), Bradford and Grosman (1982), and Vepraskas (1984). In contrast, Sands et al. (1979) found that the penetrometer resistance in a sandy soil did not differ very much over a wide range of soil wetness. Williams and Shaykewick (1970) illustrated the complex interactions between soil wetness, texture, bulk density, and soil strength.

Froehlich et al. (1980) successfully predicted compaction €or four forest soils in the Sierra-Nevada using multiple regression analysis. Sixty-nine percent of the variation in compaction by three different machines was attributed to six independent variables: number of passes, cone index (an indirect measure of soil strength), an estimate of dynamic machine pressure, soil wetness, organic matter content, and depth of litter. Two variables (number of passes and cone index) accounted for 54% of the variation. However, regression equations are characteristically specific to the area and conditions studied. They should not be applied outside the context for which they were developed, except in as much as they identify candidate independent variables to be tested.

Water movement and retention

Compacted soils have a significantly reduced rate of saturated water flow as a result of reduced macropore volume. Since compaction may not necessarily alter micropore volume, the unsaturated hydraulic conductivity may be unaffected or even increased (Greacen and Sands 1980).

In mountainous regions in coastal British Columbia, root channels and other preferred pathways in the soil may be important for infiltration and movement of water (Chamberlin 1972; de Vries and Chow 1978). Disturbance of the forest floor down to the mineral soil may close or remove a significant number of root channels, and thus reduce the rate of infiltration and subsurface flow (de Vries and Chow 1978). Surface organic layers are hydrologically important because of their water storage capacity (Golding and Stanton 1972); thus, extensive scalping may reduce soil water storage.

On specific sites, water retention may be greater when soils are compacted (Greacen and Sands 1980; Froehlich et al. 1980). Water retention may increase in compacted, sandy soils, may decrease in compacted loamy soils, and may either decrease or increase in compacted clay soils (Froehlich and McNabb 1984). The change in available soil water storage may be an important factor in early survival of tree seedlings planted on seasonally water-deficient soils.

Biomass harvesting could result in more severe compaction and scalping of surface layers and mineral soil leading to a reduction in infiltration and soil water storage when compared to conventional harvesting.

Soil temperature

Soil temperature is one of the major factors affecting 'conifer seedling regeneration in British Columbia. Dobbs and McMinn (1977) found that in the north central region of the province, low soil temperatures inhibit growth. On the southwest coastal region, Arnott (1975) reported that lethally high surface temperatures contributed to seedling mortality.

The soil thermal regime is determined by the surface heat flux density (the quantity of heat passing through a unit area of surface soil per unit time), the soil thermal conductivity (K) and its volumetric heat capacity (C). The soil thermal diffusivity (D), which equals K divided by C, indicates how quickly a temperature change will occur given the quantity of heat flowing through the soil under a given temperature gradient. The surface soil heat flux density is largely dependent on solar irradiation, convective heat transfer, latent heat transfer (evaporation or condensation), vegetative cover, and surface reflectivity (i.e., albedo). K and C are influenced by the soil bulk density and the volume fraction of air, water, organic and mineral matter present (Hanks and Ashcroft 1980; Hillel 1980; Stathers 1983).

Water has relatively high K and C when compared to air, and dry soils therefore have lower K and C than wet soils. The heat capacity, thermal conductivity, and thermal diffusivity are higher for mineral soils than for organic soils (such as forest floors or peat) at comparable water contents. Because the thermal conductivity of a soil does not increase in a linear fashion with increasing soil water content, the thermal diffusivity (recall that $D=K/C$) is also a function of soil water content and attains its maximum value at a water content somewhere in between the dry and saturated conditions (Hillel 1982).

Logging increases the surface heat flux density by removing vegetation and slash which intercept solar radiation. Convective heat transfer between the atmosphere and the soil surface will also increase following removal of vegetation and slash. Stathers (1983) found that soil surface temperature maxima increased dramatically after clearcutting a steep south-facing slope on Vancouver Island, British Columbia. On one day in August 1982, a maximum surface temperature of 64°C was recorded. The surface temperature remained in excess of 50°C for more than 7 hours. Soil temperatures were significantly lower at a depth of 15 cm where the minimum and maximum soil temperatures were 15°C and 20°C, respectively. These temperatures are below the optimum for the growth of Douglas-fir seedlings (Brix 1967; Heninger and White 1974) but the surface temperatures were lethally high (Maguire 1955; Cleary et al. 1978). Stathers concluded that high surface soil and seedling root collar temperatures were a major factor affecting seedling survival on this site. On sites where excessively high soil surface temperatures are likely to occur, biomass harvesting could negatively influence the soil thermal regime by the removal **of** shade-providing slash and reduction in the cover of advance regeneration.

Numerous operational techniques have been used **to** improve seedling survival where moisture and temperature stress **occur.** The selection **of** appropriate tree species and stock types can minimize these effects but under extreme environmental conditions additional protective measures may be necessary. These include measures that alter the seedling microclimate. Hobbs et al. (1980) found that artificial shade from shade cards increased survival on critical sites in Oregon. Stathers (1**983)** found that shade cards significantly increased the second-year survival of 1-0 Douglas-fir, western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Pacific silver fir ***(Abies** amabilis* (Dougl.) Forbes) seedlings. **Irrigation** has also been used to reduce stress (Maguire 1955). Stathers (1**983)** concluded that keeping the ground surface as rough as possible would help reduce high surface temperatures.

The evaporation rate is dependent on the surface soil water content. Vapor movement and thus cooling of the surface is reduced as the soil surface dries. Soil temperature **is** also influenced directly by precipitation and snowmelt. When water from rain or snowmelt percolates through the soil profile, **it** transports heat by mass flow.

Biomass harvesting may cause increased mineral soil exposure from additional yarding activity. The net effect on the soil thermal regime may be to increase below-surface temperatures during the active growing season. For most forest soils in British Columbia, this effect would usually be beneficial (Dobbs and McMinn 1977; Ballard 1983a).

Surface soil erosion

Surface soil erosion is primarily a concern with regard to forest road surfaces and related cut and fill slopes. Roads include primary, secondary, and spur logging roads used for hauling purposes, as well as skidroads used in ground-based yarding operations. In some instances where fine textured soils predominate, surface soil erosion may occur on disturbed or compacted areas of clearcuts (e.g., yarding trails and skidtrails). Unless raveling is the dominant erosional process, significant surface soil. erosion will only occur if the rainfall intensity or snowmelt rate exceeds the infiltration capacity **of** the soil.

Numerous site factors affect surface soil erosion. These include soil depth and water holding capacity, particle shape, amount of, and spatial and temporal distribution of precipitation or snowmelt, organic matter content, vegetative and **slash** cover, soil texture and clay mineralogy (Packer **1967;** Trott and Singer 1983). Packer **(1967)** determined that a small number of road and watershed characteristics can be used to predict road-related surface erosion. Road surface erosion is mainly affected by road grade, percentage of water-stable soil aggregates in the road surface larger than 2 mm **in** diameter, topographic position, aspect and upper-slope steepness. The characteristics that dominate sediment movement downslope from logging roads are cross-drainage spacing, downslope obstruction type, spacing and initial distance from cross-drain, fill slope cover density, road age, and percentage **of** soil particles and water-stable aggregates larger than 2 mm in diameter on adjacent undisturbed slopes (Packer 1967).

Obstructions, such **as logs** or woody residues, and depressions located on forested or road fill slopes behave **as** sediment barriers or traps (Packer and Christensen **1964;** Dissmeyer and Foster 1980; Perry and Norgren **1983).** Sediment barriers, consisting of cull logs and logging slash, constructed on the fill slopes of newly constructed forest roads adjacent to streams were found to be 75 to 85% effective **at** trapping sediment that would usually move downslope (Cook and King 1983). Logs were placed **along** the contour to trap sediment and to slow down flow on part of a municipal watershed that was burned by wildfire in central Oregon State (McCammon and Hughes 1980). Biomass harvesting would likely result **in** a reduction of logs and slash along roads which could lead to an increase in the movement of sediments from cut or fill slopes.

The Universal Soil Loss Equation **(USLE)** was developed to predict soil erosion from agricultural land. It has increasingly been used and modified to predict soil loss from forested land (Dissmeyer and Foster 1980). Factors used in the **USLE** include rainfall erosivity, soil erodibility, slope length and gradient, and cover and management conditions. Soil erodibility can be defined as the inherent difference **in** the rate of soil erosion of dissimilar soils due to intrinsic soil properties. **Soil** erodibility for a number of California range and forest soils (on a mass basis) was found to be a function of clay mineralogy, **bulk** density, a texture parameter (a function **of** percentage sand and silt), and pyrophosphate-extractable Fe and Al (Trott and Singer 1983). Of the factors listed above, only soil erodibility (i.e., bulk density) and cover and management conditions could be affected by harvesting activities. Biomass harvesting techniques that would promote increased soil disturbance or soil compaction have the potential for increasing the erodibility of forest soils by reducing the infiltration and permeability and reducing the percentage of cover (vegetation and woody material) that protects the soil surface.

Soil mass movement

Sensitivity to soil mass movement can also be affected by timber harvesting. Several types of mass movement occurring in British Columbia are summarized in Table 1.

Mass movement (taken to be synonymous with "mass wasting") is the dominant geomorphic process in coastal British Columbia. For example, Gimbarzevsky (1983) located over 8000 mass wasting events on the Queen Charlotte Islands using 1:50000 panchromatic aerial photographs. Such events (as listed in Table 1) transport large quantities of eroded materials from hillslopes to valley bottoms, thereby affecting stream water quality as well as the productivity of forest sites. Recent investigations of environmental geology and soil mass movements in coastal areas of British Columbia include Alley and Thomson (1978), Howes (1981), Wilford and Schwab (1982) and Church (1983). Important factors governing the magnitude of mass wasting include slope gradient, aspect, surficial material, underlying bedrock, hydrologic conditions, and vegetative cover. Many studies have shown increased frequency of small shallow landslides with time after logging (O'Loughlin 1972; Swanston 1974; Burroughs and Thomas 1977; Ziemer and Swanston 1977; Megahan et al. 1978; Wu and Swanston 1980; Gray and Megahan 1981; O'Loughlin and Ziemer 1982; Wilford and Schwab 1982). These studies indicate that slope stability on many steep forested lands may depend primarily on reinforcement from tree roots (O'Loughlin and Ziemer 1982) and that this reinforcement decreases as roots on logged sites decay. The studies are not conclusive because other changes are occurring simultaneously (e.g., variation in evapo-transpiration) and because most studies have not been normalized to account for differences in precipitation pattems from year to year.

Sidle (1980) reported that road building is a primary cause of accelerated erosion. In a landslide inventory, Megahan (1981) found that only 9 of 89 landslides were not associated with roads. Reed et al. (1981) concluded that road associated mass wasting was responsible for approximately 60% of the erosion damage in Clearwater River basin, Washington Swanston and Swanson (1976) reported that mass wasting rates in clearcuts were 2.2 to 3.7 times greater, and from roads 25.2 to 34.4 times greater, than on undisturbed forest slopes in Oregon, Washington, and south-coastal British Columbia. In a study on the Queen Charlotte Islands, Rood (1984) estimated that clearcut logging accelerated the frequency of landslides by 34 times. Landslide inventories based on aerial photography alone may underestimate the frequency of small landslides occurring on undisturbed forest slopes because of difficulty in identification due to canopy cover, sun shadow effects, ground slope, etc. (Schroeder and Brown 1984; Pyles and Froehlich 1987). A thorough discussion of mass wasting and land use has been provided by Sidle et al. (1985).

In soil mechanics and engineering, slope stability is expressed by a factor of safety (F), defined as the ratio of the soil shear strength to shear stress that exists on a failure plane (Terzaghi and Peck 1967). A slope is stable when this ratio exceeds one. Ballard (1983b) gives a useful expression and explanation for the factor of safety for infinite slope shear failures:

$$F = \frac{((W\cos\alpha - u)\tan\phi) + C + Cc + R}{W\sin\alpha}$$

Where W is the weight of the soil and its associated load per unit area, α is the slope of the shear plane, u is the pore water pressure at the shear plane, ϕ is the angle of intemal friction, C is soil cohesive strength, Cc is the soil strength component attributable to interparticle cementation, and R is the component of shear strength contributed by roots growing across the shear plane.

Timber harvesting and road construction can affect F by:

a) Reducing W by removing material (timber, soil, etc.) or increasing W by loading a slope with road fill or debris. The resulting change in F can be positive, negative or negligible.

b) Increasing u through reduced evapotranspiration or by concentrating surface waters from road drainage systems. Increases in u can reduce F significantly and may trigger failures.

c) Reducing R as a result of root decay (Bishop and Stevens 1964; O'Loughlin 1972; Ziemer 1981; McColl 1983).

Table 1. Common types of soil mass movement in British Columbia[a]

Type of movement	Type of material		Other characteristics
	Bedrock	Unconsolidated	
Falling	Rockfall	Dry ravel (gravel)	Very rapid and dry
		Debris fall (other)	
Sliding	Rock slump	Slump	Cohesion retained; imperceptible to very rapid
	Rockslide	Debris slide	Disintegrates, usually very rapid
Flow	Earthflow (weathered bedrock)	Earthflow	Imperceptible
		Debris flow	Rapid
		Debris torrent[b]	Very rapid
Creep		Soil creep	Imperceptible; moisture content (water and ice) varies
Complex	Some large landslides[c]	Solifluction	Imperceptible; moist (water and ice)
	Slump-earthflow	Slump-earthflow	Imperceptible to rapid; moist

[a] Source: Ryder 1983

[b] The moisture content of debris torrents is so great that flowing water is actually an agent of transportation. However, a complete gradation exists between debris torrents, flows, and slides, and so debris torrents are listed here for the *sake* of completeness.

[c] The term "landslide" is used to refer to large and complex mass movements, and also as a popular name for large slumps, slides, and earthflows.

The above equation does not consider undercutting of slopes by roads or stream bank erosion which may cause failure by removal of support. Shock from equipment or blasting can also trigger flows of material by the process of liquefaction. This occurs most commonly in recently deposited, structureless, uncompacted fill material below the water table (Terzaghi and Peck **1967).** Liquefaction is not a common kind of mass movement associated with timber harvesting.

Because most accelerated mass wasting is associated with road building, unless biomass harvesting involves expansion of road networks it appears unlikely that it would result in increased mass wasting. Extensive whole-tree utilization could result in accelerated mass wasting due to disturbance during stump extraction, reduced soil reinforcement by tree roots, and perhaps removal of most of the protective covering of logging slash. However, it is doubtful that whole-tree utilization'would be operationally feasible on steep, sensitive terrain.

Effects on tree growth

Soil disturbance caused by harvesting often increases the chances of seedling establishment and may, through reduction of organic layers and competing vegetation, increase productivity of trees at least in the short term. More often, however, studies have shown that physical and other impacts result in lower productivity. McNabb and Campbell (1**985)** outlined some of the problems in quantifying impacts on soil productivity when faced with confounding effects. Growth losses of commercial tree species resulting from site degradation have been reported by Hatchell et al. (1970), Moehring and Rawls (1970), and Wert and Thomas (1981). Losses were attributed to reduced soil aeration, infiltrability and root growth. Moehring and Rawls (1970) also observed that associated reductions of tree vigor may increase the incidence of insect and disease attack. In southeastern British Columbia, Smith and Wass (1979, 1980) found reductions in tree growth on skidroads in the majority of clearcuts studied and no impact or even enhanced growth on skidroads in a fewer number of cases. Differences in these results were related to climatic regime, topography, and soil. Estimates on the duration of such effects of up to 40 years have been made by Hatchell et al. (1970) and Dickerson (1976).

Several studies define critical values for bulk density above which root growth and development are affected (Mitchell et al. 1982; Gent et al. 1983). Bulk densities above **1.4** Mg/m^3 restrict loblolly pine **(Pinus** *taeda* L.) root growth branching and soil penetration ability. Hildebrand **(1983)** found that a bulk density value of 1.25 **Mg/m^3** in loamy soils hindered root penetration and development of beech seedlings. Minko (1975) reported that 1.5 Mg/m^3 was a critical bulk density for radiata pine (Pinus radiata D. Don) in silty-clay nursery soils and Heilman **(1981)** demonstrated a decline in Douglas-fir seedling root penetration in loam and sandy loam soils as bulk densities increased from **1.33** to 1.77 Mg/m^3. Halverson and **Zisa** (1982) showed a marked reduction in root growth of Pinus seedlings as bulk densities were increased from 1.2 to 1.8 Mg/m^3. **Carr** (1985, 1987) found that lodgepole pine (Pinus *contorta* Dougl. *var. latifolia* Engelm.) could establish and **grow** in soils with bulk densities greater than 1.5 Mg/m^3, but height growth was adversely affected, likely due to the combined effects of restricted root development and localized nutrient depletion around the seedling roots. Froehlich et al. (1986) predicted a reduction in total volume growth of 20% for an increase in bulk density from less than 1.0 Mg/m^3 to 1.07 Mg/m^3 for 9- to 18-year-old ponderosa pine ***(Pinus*** ponderosa Laws.) trees growing on skid trails in south central Washington State. However, for a higher elevation site, growth of lodgepole pine trees was not affected by a comparable increase in bulk density. Stransky **(198**1) reported increased height growth of pine seedlings on soils compacted during site preparation. This effect was attributed mainly to a reduction in competing vegetation.

Scalping of surface mineral horizons, exposing subsoil with relatively poor physical and chemical properties as the growth medium for the next rotation is another potentially harmful impact of harvesting or site preparation. It is a major concern where extensive areas are scalped, such as along tractor skidroads on steep slopes, particularly where subsoils are calcareous, shallow or coarse textured or strongly podzolized (Smith and Wass 1979, 1980, 1985) and in some mechanical site preparation treatments (Herring and McMinn 1980). According to Carr (1985), effects include regeneration delays, decreased stocking levels, decreased growth rates and some portions of scours that are simply non-stockable. Surveys by Smith and Wass (1976) in Southeastern British Columbia, however, showed higher average stocking levels on skidroads than undisturbed surfaces.

In mountainous areas of British Columbia, diversion of seepage water (and associated nutrients) by road drainage systems is also a source of concern with respect to growth losses (Survey of B.C. Ministry of Forests pedologists, reported by Ballard 1983a), but few research projects have been directed toward this issue.

Megahan (1972) showed that seepage interception **by** forest roads on sloping ground in the Idaho Batholith can rob below-road soil **of an** appreciable proportion **of** subsurface **flow.** Since seepage is a source of **both** water and nutrients (Ballard and Cole 1974), such interception has potential effects **on** productivity of sites below roads. Evidence for this is inconclusive and seemingly contradictory. Pfister (1969) reported an increase in growth in a band of trees adjacent tu the lower edge of logging roads built on volcanic ash and glacial outwash soils which he attributed mainly to increased water availability. Smith and Wass **(1979, 1980)** found no significant differences in height growth **of** trees above and below contour skidroads in any of **15** widely dispersed clearcuts in southeastern British Columbia. They **(1980)** also reported, however, better growth of trees situated in portions of cutovers lacking skidroads compared with the growth of trees between skidroads in adjacent portions of the same cutovers, but differences were significant **for** only one of three sites.

Miles et al. (1984) found that impacts associated with landslides in the western Oregon Cascades had a significantly detrimental effect **on** the height growth and stocking level of second growth Douglas-fir plantations. Average height growth of 5- to 18-year-old Douglas-fir trees on landslide scars was reduced to 62% of that **of** trees in clearcuts. The average stocking level was also reduced by 25% from the clearcut level. In the Queen Charlotte Islands, Smith et al. (1984, 1986) determined that total wood volume produced on 40- to 50-year-old landslides was reduced by 70% when compared with clearcuts of the same age.

Discussion and summary

Biomass harvesting appears to be feasible in the medium to long term, particularly in parts of south-coastal British Columbia (Blakeney **1980;** Jones 1979; McDaniels 1981, 1982). **As** discussed in this report, biomass harvesting would likely involve recovery of small stemwood pieces and larger, poor quality stemwood from landings and near haulroads and skidroads. Systems used for harvesting would be similar to those described by Blakeney (1980) and Sinclair **(1984).** Utilization of stumps extracted during root-disease control operations is also possible.

The potential impacts of biomass harvesting on physical soil properties have had to be extrapolated from the numerous studies addressing conventional harvesting. These studies show that logging operations can affect soil structure, porosity, pore size distribution, aeration, water retention, hydraulic conductivity and infiltrability. Soil thermal properties are also altered. Most attention has been directed at the amount and degree of soil disturbance, e.g., displacement and compaction, caused by different yarding methods and at the sensitivity of sites to impacts.

Soil degradation **from** harvesting and mechanical site preparation has been widely reported in the literature and in some cases estimates of growth losses have been made (Froehlich **1979;** Smith and Wass **1979, 1980;** Raghevan et al. **1981;** Terry and Campbell **1981;** Wert and Thomas **1981).** Most serious degradation results from severe soil disturbance (scalping, compaction and puddling) associated with landings **and** skidroads. Also in this category are landslides triggered by harvesting operations (Rood **1984;** Smith et al. 1986).

Biomass harvesting would likely have a range **of** impacts on soil physical properties depending on the degree **of** utilization and the harvesting methods used. Whole-tree harvesting including root systems would result in severe soil disturbance (Smith and Wass 1983), whereas recovery of some extra stemwood might result in only marginally increased disturbance with little or no increase in adverse impacts over conventional harvesting. The amount of additional soil disturbance would also depend on the location of the wood being recovered, i.e., whether it is concentrated along roads and on landings or dispersed throughout the clearcuts. With normal ditch maintenance, the recovery of roadside material would have little impact in the form of road drainage problems and road-related failures, but an increase in the amount of surface soil erosion on road cut and fill slopes may occur. Recovery of dispersed wood would affect one **or** more of the following: (1) an increase in traffic on conventionally built roads, skidroads and trails, (2) an increase in the density ***of*** skidroads and yarding trails to enable recovery **of** short logs, and **(3)** a shift from conventional cable yarding **to** a ground-based system.

Physical impacts on soils apart from those caused by conventional harvesting would have both favourable and unfavourable effects on forest productivity. Potential beneficial responses from increased mineral soil exposure include increased chances of natural tree seedling establishment, reduction of vegetative competition and increased growing season soil temperature. Increased compaction of loose soil will increase microporosity and water retention and may improve the chances of survival of seedlings in water-deficient sites, Detrimental effects are most likely to originate from increases in the degree and extent of deeply displaced and severely compacted soils and from increased potential for drainage disruption, overland flow and surface erosion. Additional road construction would increase the potential for road-related mass wasting. Reduction of ground cover may also increase the incidence of lethally high surface-soil temperatures.

Many authors suggest minimizing the amount of disturbance as the best solution to soil degradation problems (Froehlich and McNabb 1984; Smith and Wass 1985). This is reasonable as a parallel idea to "zero tillage" practiced in agriculture (Hillel 1980) and also with respect to some past forestry practices where machinery was haphazardly used with little regard to site conditions or the soil resource. Effective operational guidelines for avoidance and mitigation have been developed (Packer 1967; Murray 1976; Megahan 1977; Rothwell 1978; Carr 1980; Carr and Ballard 1980; Krag 1980; Moore 1980; Toews and Brownlee 1981; Breadon 1983; B.C. Ministry of Forests and Lands 1987). However, the benefits of reducing degradation must be compared with the costs of obtaining this reduction and with the benefits obtained from forest management operations (Ballard 1983a). For example, Standish (1984) compared the present value of future stumpage foregone from soil degradation to the added cost of reducing disturbance (by using cable yarding systems) in a mountainous area in the interior of British Columbia. He concluded that the added cost of cable yarding exceeded the present value of foregone stumpage until levels of disturbance reached 50% or more, for the following assumptions: high stumpage values, low. interest rate, and an ample allowance for soil degradation. A more complete analysis might consider the costs of off-site effects and the benefits of site rehabilitation on disturbed soils or alternative actions such as thinning and fertilization on areas of undisturbed soil. However, the calculations are generally instructive since they emphasize the importance of costs in determining the extent to which losses from soil degradation can be reduced.

The additional impacts of biomass harvesting on physical soil properties would normally be small relative to those happening with conventional harvesting. However, even small increases could result in soil disturbance levels that exceed maximum acceptable limits such as are being defined under B.C. Ministry of Forests and Lands policy (B.C. Ministry of Forests and Lands 1987). Biomass harvesting considerations would have to be included in preharvest planning and cutting-plan approval procedures. In addition to economic criteria, the degree to which additional wood could be recovered would depend on the environmental sensitivity of the site. For instance, recovery of whole stem and stump/root systems would likely have to be restricted to well drained, gently sloping and generally robust sites.

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