Fundy Model Forest

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Protection of soil quality for sustainable forest management
-soil compaction, erosion and displacement-

Prepared for:
The Fundy Model Forest
Soil and Water Conservation Committee

By
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Executive Summary

Soils often suffer adverse changes during forest harvesting and renewal, including compaction, erosion and displacement. The purpose of this report was to clarify the nature and extent of these processes, to appraise the potential for damage, to examine ways of prevention and opportunities for mitigation, and to consider the implications for the Fundy Model Forest.

Compaction of soils has been noted since the early use of tracked and wheeled equipment in forest harvesting. The effects were consistent from the southeastern states through the Pacific Northwest and Canadian forest regions. Up to 20% of the area of a clear-cut could be affected. Natural regrowth and early plantation development was retarded as a result of it, and volume loss was recorded in 40-year-old and older stands on the affected areas.

Surface erosion develops on skid and porter trails, wood yards and landings if environmental constraints such as slope and inherent erodibility of the soil are ignored and mitigating measures not taken. More often than not, a displacement of soil is involved where elevated or steeply sloping portions are denuded of their colloidal, fine sand and silt fractions, to be redeposited at low slope, in filter and buffer zones. As a result, increasing heterogeneity can be expected in future production on the affected lands. **Mass erosion**, involving landslides and slumping of soil, diminish productivity in the scour zones and produce catastrophic effects on water quality where the soil is entered directly into water courses. In regions prone to mass erosion, the natural frequency of events is increased many times by harvesting activities, particularly road construction. Mass erosion is a hazard in landscapes with excessive relief, high rainfall amount and intensity, and soils

of low mechanical strength.

Soil compaction and surface erosion pose a certain threat to sustainable site productivity in parts of the **Fundy Model Forest.** Among the soils mapped in the region are some with high susceptibility to compaction. Some are more disposed than others to surface erosion after disturbance in a landscape of stronger than average relief because of varying inherent erodibility. No information exists to verify these hazards.

Many jurisdictions on the Continent have issued best management practices (BMPs) to prevent and mitigate damages to the forest environment. Current BMPs, particularly those dealing with erosion, where primarily aimed at preserving aquatic systems. It is not certain whether they also provide for adequate protection of soil quality.

With respect to the Fundy Model Forest, this review has verified several needs: (1) to assess actual levels of soil compaction and surface erosion under current methods of forest harvesting and renewal; (2) to review, revise and supplement, where necessary, known BMPs for use in the region; and (3) to confirm BMPs and determine level of compliance by operators.

Table of Contents

List of Figures

Introduction

According to the contemporary technical literature, soils Afunction, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation@ (Allen et al. 1995). Their ability to function in this role is referred to as **soil quality** or health (Doran and Parkin 1994).

Soil quality may change in either direction as a result of human activity or natural ecosystem processes. A drastic example for the latter are the disturbances caused by severe fire and reversion of forest to heath (Damman 1971).

In managed forests, the possibility of loss of soil quality is greatest during the period of harvesting and regeneration. This was recognized by the Canadian Council of Forest Ministers (1995) by identifying **soil and water conservation** as one of six criteria for sustainable forest management.AMaintenance of the living substrate for forest stands@ or in above terms, preservation of soil quality, was given as the Aprimary focus of soil conservation@. The report further recognized processes that commonly result in a loss of soil quality (erosion, displacement, compaction, puddling and loss of organic matter), but the details, essential to problem recognition, prevention or mitigation, were left to be compiled at the regional level.

The response to a disturbance is complicated by interactions with climate, vegetation type and the nature of the soil itself. It would be difficult, indeed, to gauge the extent of damage or to establish permissible changes in soil conditions on a site-by-site basis unless guidelines existed that are sensitive to ecological and forestry conditions of the region. To this end, a review of the technical literature was conducted to clarify the nature and extent of soil dehabilitating processes during forest harvesting and renewal, to appraise the potential for damage, to examine measures of prevention and opportunities for mitigation, and to consider the implications for the Fundy Model Forest.

Soil Compaction

Definitions

Compaction of a soil is associated with the disruption of structure, loss of pore volume, primarily macro-pore space and, hence, a reduction in infiltration capacity and air permeability. At the same time, the bulk density and mechanical strength of the soil increase. All of these changes adversely affect plant establishment and growth. To be emphasized are the inhibiting effects on root growth and rhizospheric activities (Sands and Bowen 1978). Soil compaction invariably occurs during forest harvesting with heavy equipment deployed in ground operations (Graecen and Sands 1980). Equipment movement and dragging of wood may also result in a **puddling** of soil. This is the disruption of structure and reorientation of particles at high moisture content with little or no change in volume (Hillil 1980).

Case studies

Concern over soil compaction was expressed early after the introduction of crawler tractor logging in North American forests following World War II. Steinbrenner and Gessel (1955a,b) and Youngberg (1959) reported major increases in bulk density of the usually highly porous (< 0.75 Mg m^{-3})[1] and productive volcanic ash soils in the Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) region of the **Pacific Northwest**, and noted that seedling establishment and growth were seriously retarded on skid roads. From 25 to 30% of the harvested areas was found in skid roads. The problem was not lessened when rubber-tired skidders were introduced later on. Although these were lighter in weight, the wheel pressure of loaded machines could be as high or higher than under the heavier tracked vehicles (Lysne and Burditt 1983).

An impression of the potential impact of soil compaction on the

1) 1 Mg m^{-3} = 1 Megagram or 1 metric ton per cubic metre

primary production of forest in the northwestern region of the United States was given by Froehlich and McNabb (1984). Including the results from various independent studies, the relative height growth of trees in plantations was reduced in direct proportion to the relative increase in bulk density of the soil during logging (Fig. 1).

Fig. 1. Loss in height growth of Douglas-fir and Ponderosa pine with relative increase in bulk density on clear-cuts at various locations in the northwestern United States (reproduced from Froehlich and McNabb 1984).

The effects of soil compaction on forest growth can be long-lasting. Loss in height growth was recognizable in Ponderosa pine (*Pinus ponderos* Laws) plantations (included in Fig. 1) 17 years after logging, and volume production was lowered, on average, by 20% on skid trails 23 years after logging (Froehlich et al. 1986). Similar observations were made in California where 16-year-old ponderosa pine were 13% shorter and had 22% less volume on skid trails and landings, on which the average bulk density had been raised to 1.19 Mg m^{-3}, than the trees on less disturbed land (Helms and Hipkin 1986; Helms et al. 1986).

Another account of lost volume production with an even longer response period was given by Wert and Thomas (1981). Forty three years after tractor logging at a Douglas-fir site in the Coast Range of Oregon, trees were fewer in number and, on average, 3 m shorter on skid roads compared to trees on non-compacted soil. Far greater differences existed in volume production (Fig.2). On an equal-area basis, the skid roads had produced 74 % less volume than the unaffected area. With 10% of the area in identifiable skid roads and an additional 18% on an area of transition, an overall volume loss of 11.8% was estimated for the second rotation stand. Slow seedling development and growth to the breast-height stage were seen as a major cause for the reduced performance. Trees on skid roads and unaffected areas grew at similar relative rates after a certain height-age combination had been reached.

Fig. 2. Volume production, by diameter class, of Douglas-fir on skid trails and undisturbed soil 43 years after logging (from data of Wert and Thomas 1981).

Production loss due to soil compaction has also received serious attention in the **southeastern United States**. Foil and Ralston (1967) demonstrated rapid decline in the growth of loblolly pine (*Pinus taeda* L.) seedlings with increasing bulk density of the soil, and pointed out that compaction levels, shown to be critical in their study, existed on significant percentages of land areas being harvested for southern pine. This was confirmed in subsequent studies of soil disturbance by logging on the Lower Coastal Plaines of South Carolina (Hatchell et al. 1970; Dickerson 1976). Increases of bulk density by 20 and 10% where found in wheel-rutted soil and log-disturbed areas, respectively, after tree-length harvesting with rubber-tired skidders. Of further interest is that volume growth of loblolly pine was increased 100% with fertilization on skid trails, but that no fertilization responses were shown on non-compacted areas in the plantation (McKee and Hatchell 1986). It is possible that the nutrient supplements compensated for a limited root surface area in the compacted soil. This was substantiated by the observations of Helms et al. (1986) according to which the periodic height increment of ponderosa pine on compacted soil was closely correlated with mineralizable nitrogen, but exhibited only a weak, although significant correlation with bulk density.

Although investigation into soil disturbance during forest harvesting commenced at a much later time in **Canada**, results published so far indicate that soil compaction may be as common here as in the United States. A survey of cut blocks harvested with different equipment in the Nelson Forest Region of Southeastern British Columbia (Krag et al.1986) showed soil disturbance on 45% of the area from summer logging. No measurements were made for bulk density, but the high frequency of skid roads and landings, accounting for 28.8% and 5.1% of the disturbances, suggests that a considerable portion of the cut area was affected by compaction. Winter logging reduced somewhat the adverse effects of ground skidding. Improvement was greatest with cable yarding.

Determination of bulk density after clear-cutting and site preparation in west-central Alberta (Corns 1988) showed various levels of compaction. Depending on soil Association and depth (0 - 30 cm), the average bulk density was increased 0 - 39%. Increases were generally highest near the surface. The soil with the finest texture (clay loam) showed the greatest change in bulk density, and no effects of logging and site preparation were detected on well to rapidly drained sandy loam of Tertiary fluvial origin. Tests under greenhouse conditions revealed significantly decreased growth when lodge pole pine (*Pinus contorta* Loudon var.*latifolia* Engelm.) and white spruce *(Picea glauca* [Moench.] Voss*),* the dominant species at the surveyed sites, where grown on soil compacted to levels as observed in the field immediately and 5-10 years after cutting and site preparation. The author concluded that potential loss in forest productivity from soil compaction during forest harvesting and regeneration was similar to losses reported elsewhere, including the long-term studies from the United States.

The variable effect of harvesting equipment on different soils was confirmed by Startsev et al. (1998) who measured bulk densities at increasing levels of skidder traffic on clear-cuts in the same region. While loams of three different Associations showed significantly increased bulk densities after three skidder cycles, a sandy loam of a fourth Association was not affected even at 12 cycles. It was pointed out that the unaffected soil existed at lower water potential than any of the other soils at the time of the skidder traffic.

Further adding to the Canadian data base, Brais and Camire (1998) reported on soil compaction by skidder traffic in the Quebec portion of the Northern Clay Forest Section on moist, fine- and medium-texured soils. Despite adherence to Acareful@

logging methods, monitoring bulk density revealed compaction levels as observed elsewhere.

Soil compaction, as a possible cause of production loss, has received attention in **recent experiments in forest regions throughout the United states and at several locations in Canada** (Powers et al. 1990). Their purpose is to test the hypothesis that porosity, more specifically macro-pore space, and organic matter content are the two soil factors most critical to primary forest production. The value of this research lies in the use of a standard experimental design applied over a wide range of forest conditions and its long-term approach. Although work is at an early stage, the adverse effect of compaction on forest growth is clearly apparent in results published so far. For example, Stone and Elioff (1998) reported that five years a after treatment, in which the bulk density of the 15-cm surface soil had been increased by an average 22% after clear-cutting of mature aspen (*Populus tremuloides* Michx. and *P.grandidentata* Michx.) in northern Minnesota, the density of aspen suckers was reduced from 40400 to 19600 ha^{-1}. More importantly, the total sucker biomass on compacted soil was only one third of the biomass on the non-compacted soil.

Recovery of compacted soils

Soil aggregation, the opposite to compaction, is largely dependent on biological activity, primarily root growth. As pointed out earlier, root growth and rhizospheric activity are inhibited at high soil strength and a lack of macro-pore space. It should not be surprising, therefore, that compacted soils revert only slowly to the pre-harvesting condition. For sandy soils in Mississippi, a recovery time of 12 years was estimated (Dickerson 1976), but considerably more time was needed for the restoration of compacted fine soils on the Coastal Plaines in Virginia (Hatchel and Ralston 1971). Bulk density returned to pre-harvest level within 18 years on landings, but no significant trend towards recovery existed for soil on skid trails.

A texture effect was also shown by Froehlich et al. (1985) in their study of Ponderosa pine plantations on granitic and volcanic ash soils in Idaho. The logging impact on bulk density was nearly always less in the coarser soils with the granitic substrate than in the finer ash soils, and the bulk density near the surface (about 5 cm) had reverted to background within 20 years in the coarser soil. However, above-background compaction was still detected after 23 years at 15 and 30-cm depth. In contrast, the ash soils showed significant above-background compaction at all depths 23 years after the intervention. Projections from plots of bulk density vs. time indicated recovery periods of more than 30 years.

The above observations agree with the earlier data from Wert and Thomas (1981) which showed background-level bulk density in the 15-cm surface soil of skid roads, but a persistence of above-background soil density at 20- and 30-cm depth under 32-year-old Douglas-fir in the Oregon Coast Range. While investigating compaction under similar soil and forest conditions, Power (1974) found that soils of skid roads had not recovered within 40 years after logging.

Canadian observations on the persistence of soil compaction is limited to the previously cited Albertan study. Depending on the relative increase in bulk density during logging and site preparation, recovery periods varied from 12 to 21 years (Corns 1988). The recovery period was longest for a clay loam compared to silty clay and silt loam, and near the surface of the soil compared to 20- and 30-cm depths.

The generally slow recovery of compacted soils has led to the suggestion that former haul roads, landings and heavily used skid trails be ameliorated by tillage (McNabb 1994) or fertilization (McKee and Hatchell 1986). Special concern is warranted under short-rotation management. A soil may be re-compacted in the second cycle before recovery from compaction in the first cycle of harvesting has occurred.

Susceptibility of soils to compaction

The bulk density in forest soils normally varies between 0.6 and 1.2 Mg m^{-3} in mineral surface horizons, and from 1.3 and 1.7 Mg m^{-3} in sub-soil horizons. In contrast, the density of the solid soil mass normally ranges between 2.3 and 2.6 Mg m^{-3}, allowing for a pore volume of 26% to 77%. **All soils are therefore compactable under an applied stress**, but they offer variable resistance to compaction, depending on their mechanical strength. The latter is foremost a function of **texture** and **water content**.

Susceptibility to compaction is given by the **compression index** which measures the rate of change in bulk density at increasing stress. The compression index of a soil normally increases as the clay content increases from about 2 to 33%; it changes little with further increase in clay and may decrease again at very high clay content (>50%)(Larson et al. 1980; McNabb and Boersma 1993). Secondly, the compression index is highest at low water content (10-15% of saturation) and increases with increasing water content (Larson et al. 1980; McNabb and Boersma 1996). The optimum water content for compaction is at or just below at field capacity (Dekimpe et al. 1982). Saturated soils, like dry soils, are less prone to compaction, but present a condition at which puddeling and rutting occurs.

Secondary factors of soil compaction are the mineralogical composition of the clay particle-size fraction and the content of organic matter. Non-crystalline clays such as the allophanes of the volcanic ash soils and the oxides of iron and aluminum, which accumulate in the podzolic (Bf) horizons, increase soil strength (Larson et al. 1980). In contrast, layer silicates, in particular smectite-type clays, lower soil strength and increase the susceptibility to compaction.

Organic matter plays an indirect role through its effect on water retention (Dekimpe et al. 1982). The compressibility of soil at a given volumetric water content decreases with increasing organic matter content.

The texture effect on the compressibility of soils is readily apparent in the case studies reviewed above. More difficult, if at all possible, is to separate the effects of soil water content, organic matter and type of clay. Coarse fragment content (particles > 2mm), surface rooting and presence or absence of a forest floor also play a role in soil compaction, either by increasing soil strength or directly intercepting the applied stress. These variables have so far not been evaluated in a quantitative manner under field condition.

Are soils of the Fundy Model Forest prone to compaction?

I am not aware of investigations directly related to soil compaction and forest growth in the Atlantic provinces. High degree of stoniness (coarse fragment content), shallowly spread root systems and strongly developed forest floors, which usually appear as cohesive root mats, can be counted on the positive side. Also, harvesting in the low-volume forests of the east requires a lower level of machine traffic than in the high volume forests of western regions. However, with the high and evenly distributed precipitation through the seasons, high soil moisture content is maintained over significant portions of a normal year. This narrows the window for safe operation on susceptible soils.

Fundy Model Forest soils are highly variable. Features related to compressibility are weakly shown in some and strongly pronounced in others. For example, soils of the Sunbury Association, which occupy a large area in the east central portion of the Model Forest area (Fahmy and Colpitts 1995), are characterized by coarse texture, high coarse fragment content and good drainage (Rees et al.1992). It is unlikely that serious compaction results on these soils from equipment operation at any time of the year. In contrast, soils of the Stony Brook Association, which occur throughout the northwestern portion of the Model Forest, pose a high risk. These soils, being derived from red mudstones, are medium to fine texured throughout the profile, with clay contents ranging upward to 35% and coarse fragment content being less than 10%. The eluvial horizon is low in organic matter. Due to the fine texture, drainage is more often than not impeded. With the high precipitation in the region, the window for safe operation would be very narrow, if one existed at all, for an imperfectly or poorly drained Stony Brook soil. Sufficient moisture may be retained for maximum compaction even during the driest part of the year, and the probability of puddling and rutting to occur is high during periods when the soil is water-saturated but not frozen.

In short, significant landscape components of the Fundy Model Forest are deemed susceptible to soil compaction, puddling and rutting, demanding special attention in planning and execution of forestry operations.

Preventive and mitigating measures

First among measures to minimize soil compaction and possible loss of productivity is to control machine traffic (Froehlich and McNabb 1984). Where skidders are used, it is preferable to have fewer trails with heavier traffic than many trails with light traffic. This is readily apparent from Fig. 3. On an area with continuing traffic, the bulk density of the soil rises rapidly with the first few passes of the machine and increases little with further use (Hatchell et al. 1970; Froehlich and McNabb 1984; Brais and Camire 1998; Startsev and

McNabb 1998). Where operators are left to select travel routes as needed, up to 40% of the cut block may be covered by primary and secondary skid trails. Preplanning skid trails has been suggested as an alternative (Froelich and McNabb 1984). Innovations such as light-weight synthetic fiber cables and telescoping extra-long booms (Guimier and Heidersdorf 1998), may allow winching of logs over wider distances and movement of harvesters at wider spacing. It would be timely for practicing engineers and landowners from within the Fundy Model Forest to define **maximal permissible areas** for skidding or other forms of off-road transportation of wood, taking into consideration terrain variability and developments in equipment design. Their recommendations could then be tested for adoption as Best Management Practices (BMP).

A second opportunity for minimizing compaction lies in proper timing of operations. For medium- and fine-texured soils with impeded drainage (e.g. Stony Brook IV & V), it may be safe to operate machines only when the soil is frozen. To assure

continuity in the flow of wood, forest on less susceptible soils (e.g. Sunbury, Parleeville) might be scheduled for harvest during the wettest and most critical periods of the year (spring and late fall), leaving terrain with little to moderately susceptible soils for the normally drier summer and early fall weather. Guidelines for seasonal **scheduling** of harvesting operations to minimize soil compaction could also take the form of BMPs. A rating of the Model Forest soils with respect to sensitivity to compaction would facilitate this process.

While conditions presently exist for applying any of the above suggestions, further opportunities lie in the design of future equipment, favoring machines with low ground pressure.

Measuring soil compaction after logging

Soil compaction is measured directly by determining the change of bulk density or indirectly by measuring penetrometer resistance. Determination of bulk density in the persistently stony soils of the region requires special methods which are tedious and not applicable to routine surveys of forest land. Penetrometer readings are obtained more readily, but have little meaning when taken in stony soils.

Since compaction results from wheeled and tracked equipment, it is proposed that the **total area affected by machine traffic** is determined as the first estimator of the extent of soil compaction on a cut block. Recalling that most of the compaction is produced in the first few passes of the machine (Fig. 3), the intensity of traffic (total number of passes over the same groung) becomes less important. It should be possible to refine the area-estimate of compaction by taking into consideration the **ground pressure** exerted by the (loaded) machines and the **compressibility** of the soil. A coefficient of 0 for light or specially eqipped machines or soil of very low compressibility would then yield zero compaction impact, regardless of the area affected. Models published by McNabb and Boersma (1996) may be tested to define compressibility. Area affected by machine traffic is easily determined in ground surveys, following published procedures for estimating soil disturbance after forest harvesting (Dyrness 1965; Bockheim et al. 1975; Smith and Wass 1976; Krag et al. 1986). It should also be interesting to check whether the resolution of aerial photographs, taken after completion of a harvesting operation, allows a monitoring of machine traffic.

Soil Erosion

Definitions

Forest soils normally have high infiltration capacities (Dyrness 1969; Johnson and Beschta 1980) due to the ubiquitous presence of litter and humus layers which protect the mineral soil from dispersal and crusting under the force of falling rain drops and crown drip. Drainage of excess water occurs mainly in subsurface flow (Beasley 1976; Luxmore et al. 1990) so that precipitation, even at high intensity, rarely generates overland flow and soil erosion. However, overland flow and **surface erosion** occur when the mineral soil is beared by natural or man-caused disturbances, in particular forest harvesting and site preparation for planting.

A more dramatic form of erosion is the **mass movement** of soil in creep, slumping and debris avalanches or flows (Swanston 1978). These are natural processes occurring under certain terrain and climatic conditions, but the frequency of their occurrence can be largely increased by forest harvesting.

Surface erosion

Sediment yield from a watershed of known area has often been used as a first approximation to soil erosion. Sediment yield, thus is the mass of suspended solids discharged within a certain period of time per unit area of watershed plus the bedload of the stream (accumulated sediment above weir) divided by the size of the watershed.

Generally low sediment yields have confirmed the stability of soils under a protective forest vegetation. For example, Lull and Reinhart (1972) gave a range of 0.045 to 0.067 Mg ha^{-1} yr^{-1} for sediment yield from forested, undisturbed watersheds in the eastern United States. At these low levels, erosion does practically not exist. Locally derived information conforms to this observation. In Hayden Brook, which drained one of the paired watersheds in a central New Brunswick study of the effects of clear-cutting on water quality (Anon. undated), suspended solids ranged from <1 to 5.1 mg L^{-1} over seven years of baseline monitoring (Krause and King 1981). The corresponding sediment yield (not computed) would have been at the low end of the range of values published from the eastern United States. Similarly low values for suspended solids are shown for the pre-disturbance period of water quality monitoring in the buffer zone management case study at Hayward Brook in the Fundy Model Forest (Krause 1997).

Effect of Forest harvesting. Increased sediment yield was detected after logging in four out of sixteen small watersheds on granitic soils in central Idaho (Haupt and Kidd 1965). The effect of the disturbance on sediment yield lasted for three years. In another study of logging in a high-elevation watershed in Colorado, sediment yield was increased 2.3 times, but with a low pre-disturbance record, the average yield during the response period was only 0.224 Mg ha^{-1} yr^{-1} (Leaf 1966). Sediment flow was highest during and after the year of intervention and increased rapidly to background level in subsequent years. In a 35-ha watershed of West Virginia, sediment yield rose 1.7 times above control during an 8-year period following selection cutting, and 2.5 times in the next 7-year period following clear-cutting (Patric 1980). The increased sediment loading was viewed as a minor and short-lived effect, falling within the natural range of the geologic erosion rate for the region.

Although sediment yields were not specified, temporary surges in concentration of suspended solids indicate similar effects in many of the controlled watershed studies conducted in the past few decades in the United States and Canada (cf. Krause and King 1981; Plamondon et al. 1982; Hornbeck et al. 1986; Swanson et al. 1986).

Sediment yields at above levels may temporarily impair water quality, but do not necessarily indicate an erosion problem in the watershed as a whole. In this context, it should be recalled that the major share of sediment usually originates on haul roads and from disturbances along road right-of-ways. In steep terrain of southern Idaho, surface erosion was increased 1.6 times over background during a 6-year period on an area with ground cable logging. In contrast, the corresponding rate of erosion on roads servicing the same operation was

220 times higher than background (Megahan and Kidd 1972). The dominating effect of road construction and use on sediment yield has been recognized in numerous studies (e.g. Haupt and Kidd 1965; Leaf 1966; Frederiksen 1975; Hetherington 1976; Rothwell 1977; Reid and Dunne 1984)

Using a different approach , Johnson and Beschta (1980) assessed soil loss during and after logging by use of infiltrometers, randomly distributed over clear-cuts of Douglas fir forest in western Oregon. They found that sediment load in the average run-off from infiltrometers was increased from about 200 mg L^{-1} under forested condition to about 1500 mg L^{-1} on tractor clear-cuts. Interestingly, sediment loads were not increased significantly above background by cable-logging. Soil movement thus detected occurred mainly on skid trails, which comprised 50% of the sample plots. Typically, the infiltration capacity of these plots had been reduced due to compaction of the soil by the wheeled equipment. The mobilized soil was not necessarily lost from the land, but partly redistributed as sediment loaded water was diverted and slowed by logging debris.

A large discrepancy between sediment yield and actual movement of soil was also shown by Clayton (1981). Clear-cutting, helicopter yarding and slash burning in mountainous terrain of Idaho accelerated erosion to 1.8 Mg ha^{-1} over the first winter, 13 Mg ha^{-1} during the following summer and 4 Mg ha^{-1} over the second winter and summer. These amounts were many times higher than the discharge of suspended solids at the mouth of the watershed because of on-slope (behind cull logs) and in-channel storage.

The above observations suggest that denudation and redeposition of soil are not uncommon processes and that the intensity and frequency of occurrence are likely to vary with terrain condition and method of harvesting. Unfortunately, few investigations into the environmental effects of forestry practices have assessed soil movement directly. Conclusion may carefully be drawn from surveys of soil disturbance. For example, summarizing the effects of logging operations with ground skidding in the Nelson Forest Region of British Columbia, Krag et al. (1986) reported that an average 29% of the cut area were in skid roads. On one third of the skid roads, the soil had been disturbed deeply (>25cm). Deep disturbance occurred more frequently on steep slopes (40%+) than low slopes. These are conditions highly conducive to localized soil erosion, on-slope and riparian zone redeposition, and sediment loading of streams.

There are good chances that mineral soil exposure and subsequent erosion are minimized with the increasing use of short-wood processors. Nevertheless, opportunities for erosion can arise on porter trails, especially when their orientation is up and down slopes (Fig. 4).

Effect of site preparation. Accelerated soil movement has been reported after intensive **mechanical** site preparation and under certain conditions of **slash burning**. An example of heavy erosion is given by a case study from Mississippi (Beasley 1979). Sediment yields of about 12 Mg ha^{-1} were recorded from small watersheds during the year following site preparation by chopping and burning or by shearing, windrowing and burning. Discing after shearing and burning, to form beds for planting, further raised sediment yield to about 14 Mg ha^{-1}. Sediment yields diminished to about 2 and 5 Mg ha^{-1} during the second year in the watersheds with the non-bedding and bedding methods of site preparation. It should be emphasized that this study was conducted in watersheds with strong slopes and highly erosive soils.

Site preparation with windrowing, burning and bedding of soil also produced high sediment yield (about 8 Mg ha^{-1}) in a case study from the Piedmont plateau (Douglas and Goodwin 1980), but soil movement was within acceptable limits (<1 Mg ha^{-1}) when sites were prepared by similar methods in low-slope Coastal Plain terrain of the south eastern United States (Hollis et al. 1979; Beasley and Granillo 1988).

Erosion induced by mechanical site preparation appears to be less common in Canadian forest regions. Soil is less intensively manipulated by methods presently employed and soils are less erosive than in the southeastern pine regions. However, erosion and redistribution of soil undoubtedly resulted from the deployment of heavy plows under certain terrain conditions during the early stages of reforestation in the Atlantic provinces (Fig.5).

Slash burning has not infrequently been shown to increase the erosion hazard. Fredriksen et al. (1975) reported the largest peaks of suspended stream sediment after slash burning on a clear-cut in an experimental watershed in the Oregon Coastal ranges. Another example of increased sediment flow after slash burning was reported from a case study in the Coastal Hemlock-Spruce forest of southern Alaska (Stednick et al. 1982). Sediment loads of the stream draining the clear-cut watershed rose to 1286 mg L^{-1}. Hot fires expose the mineral soil and effectively lower the infiltration capacity by rendering the soil hydrophobic (Debano and Rice 1973).

Mass movement

Mass movement of soil has devastated aquatic habitat, produced sedimentation in reservoirs and adversely affected forest growth (Dyrness 1967; Swanston 1974; Fredriksen et al. 1975; Roberts and Church 1986). Not only are valuable timber resources lost in the event, but forest regeneration is delayed and productivity lowered on the scour zones of slumps, debris avalanches and flows (Miles et al. 1984). The reasons obviously are loss of fertile surface soil and limitation to rooting on the denser substrate of the scoured land (Adams and Sidle 1987).

Mass movement of soil and its implications to forestry have been investigated most extensively in the Rocky Mountain and Pacific Coastal Ranges of North America. For example, Dyrness (1967) reported an event from the Cascade Mountains in Oregon in which 266 000 m^3 of soil were moved by 47 slumps and debris avalanches, collectively referred to as landslides, within a 6100-ha drainage area. About 64% of the mobilized soil entered the water courses directly. More than 72% of the slides were related to roads which comprised less than 2% of the total drainage area, 17% of the slides happened on logged areas covering about 14% of the total area, and less than 11% occurred on the remaining non-logged portion (about 85% of the total area).

Fig. 4. Regenerating clear-cut with detectable erosion in uphill porter trails (middle). (Foreground shows recent cutblock with buffer destroyed by wind).

Fig. 5. Soil erosion after site preparation with Finnish plow in undulating terrain. (Note locations of denudation and redeposition).

A second example was given by Megahan et al. (1978) from the Idaho Batholith in the Rocky Mountains. During a 3-year observation period, the occurrence of 1418 landslides was recorded within an area of approximately 6000 km^2. The average slide was 17 m in length and width, and 1.5 m in depth at the failure zone. It had a total volume of 460 m^3 of which about 19% was delivered to active stream channels. Removal of the forest cover by logging accounted for 2% of the slides, but with subsequent burning the incidence of slides was increased to 9%. Roads were associated with 88% of all landslides. Only 3% of the slides occurred on totally undisturbed land.

Frequency and type of mass movement of soil basically depend on topography (relief and slope), bedrock geology, soil properties, pattern of precipitation and the stabilizing influence of the vegetation. **Relief** and **slope** feature most prominently in mass movement. The previously mentioned survey in the Oregon Cascades (Dyrness 1967) revealed that the majority of landslides (83%) occurred on slopes of 45% or steeper. Similarly, the frequency of slides was greatest at grades between 50 and 80% in the Idaho Batholith terrain (Megahan et al. 1978). This survey further showed that the incidence of slides increased steadily from the upper to lower third of the slope.

Bedrock geology and **soil** parent material were recognized as decisive factors in most studies of mass movement. In the example from the Cascades (Dyrness 1967), slides occurred mainly on pyroclastic deposits, including tuffs and breccias, and only infrequently on the more common basalt and andesite formations. Within the former class, the shear strength of the soil was further lowered and the probability of slope failure increased by the presence of smectite-type (shrinking and swelling) clay minerals (Paeth et al. 1971; Taskey et al. 1978). In their assessment of the land slide hazard in the Rocky Mountains, Megahan et al. (1978) found that the frequency increased with increasing degree of fracturing of metamorphic bedrock and increasing degree of weathering on granite. The incidence of slides was probably also higher on metamorphic bedrock because of the finer regolity and soils associated with it.

The type of mass movement is largely determined by the nature of the regolith (Swanston 1978). Shallow, coarse-texured and cohesionless deposits of glacial or colluvial origin over smooth bedrock or compacted till give rise to debris avalanches. In contrast, deep and fine deposits, derived from weathering *in situ* or being of glacio-lacustrian or aeolian origin, are subject to creep and slumping.

Critical to mass movement of all kinds is the water content of the soil. A soil=s resistance to the gravitational shear stress decreases as it becomes water saturated and free water accumulates in its macro pores, creating a buoyancy effect. Thus, the more porous a soil the greater is the hazard of slope failure (Sauder et al. 1987). The buoyancy effect helps to explain the high incidence of slides in the Cascade Ranges of the Pacific Northwest where soils of pyroclastic origin with typically low bulk density frequently dominate the landscape. The landslide hazard is further increased by the intensive and prolonged rainfall events in late fall and winter and by up-slope seepage water (Megahan et al. 1978).

Slope failure at increased frequency after clear-cutting is partly explained by the loss of mechanical slope support through root decay. According to Swanston (1974), the shear strength of soil is reduced to its minimum within 3 to 5 years after clear-cutting which matches the pattern of root decay. Roots, 1 cm and less in diameter, were considered as most effective for developing slope stability by Bourroughs and Thomas (1977). Beschta (1978) also attributed slope failure to the loss of tensile strength in decaying roots. Lowering of the evapo-transpirational loss with resulting increase in soil moisture further reduces slope stability after clear-cutting on slide-prone sites.

The increased incidence of landslides after road building is often explained by undercutting of toe slopes and piling of rock and soil debris on unstable substrate (Swanston and Swanson 1976). Road building activity also modifies drainage conditions, routing additional water into slide-prone areas and increasing the hydrostatic pressure in the unstable soil masses. Slides and slumping occur more often on cut-slopes than fill slopes and are less frequent with installation of culverts (Megahan et al. 1978). The same authors also noted that the frequency of slides rose with road standards, i.e., a terminal road with limited excavation would normally produce less mass movement of soil than arterial roads, designed for high speed and requiring extensive excavation.

Assessing the Erosion Hazard in the Fundy Model Forest

For land under agricultural management, the erosion hazard is routinely assessed by use of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) in which the potential soil loss (PSL) is a function of the rainfall(R), inherent erodibility (K), slope (S), vegetative cover (C) and conservation practices factor (P).

$$PSL = R\ K\ S\ C\ P$$

The **rainfall factor**, determined by the intensity and duration of rainfall events, increases from about 72 in the northern and central portions of the Model Forest to about 100 near the Fundy Coast (Wall et al. 1983), and it rises steadily southwards, reaching a maximum of 600 in the southeastern states from where excessive erosion losses were reported after site preparation.

A soil=s inherent **erodibility** (K) increases with the content of silt + very fine sand and decreases with the contents of clay, organic matter, coarse fragments and permeability. The beneficial effect of coarse fragments was verified with several Canadian soils in trials with in trials with simulated rainfall (Chow and Rees 1995). Values of K determined by an empirical function (Vold et al.1985) for common soils in the Fundy Model Forest ranged from 0.03 to 0.52. For comparison, K for selected agricultural soils in the eastern United States varied between 0.38 and 1.1 (Thompson and Troeh 1978).

The **slope** factor is determined by steepness and length. It is equal to 1 for a 9% slope of 22 m length, and increases exponentially with increasing steepness and the square root of the ratio of actual to standard (22 m) slope length.

The following is a comparison of selected soils from the Fundy Model Forest area with respect to erosion hazard. PSL values were calculated assuming 50 m slope length and complete exposure of the mineral soil.

Among the soils with the lowest PSL are those belonging to the Reece and Sunbury Associations, mapped in the east central portion of the Model Forest (Fahmy and Colpitts 1995). Under conditions of the modal pedon for a well drained Reece soil at 3% slope (Rees et al. 1992), the PSL amounts to 2.5 Mg ha^{-1} yr^{-1}. The corresponding value for a Sunbury soil is 4.5 Mg ha^{-1} yr^{-1} on a 4% slope. Soil losses of this magnitude may be sufficient to temporarily alter water quality in an adjacent stream, but are deemed **negligible** in agricultural land management (Vold et al. 1985).

Harcourt soils are normally restricted to terrain of low relief. They nevertheless pose an erosion hazard because of a high inherent erodibility. Using as example a well to moderately well drained variant on a 4% slope in the Grand Lake Ecodistrict (Rees et al. 1992), a PSL of 21 Mg ha^{-1} yr^{-1}. was calculated. This is considered a **moderately severe** erosion hazard in agricultural land management.

As would be expected, the potential for surface erosion increases in the rolling and hilly landscapes of the Anagance Ridge Ecodistrict of the Model Forest. Considering again conditions of a modal pedon for a well drained soil of the Parry Association (Holmstrom 1986), the PSL, at 10% slope was 23 Mg ha^{-1} yr^{-1}. This represents a **severe** erosion hazard by agricultural standards. In contrast, the erosion hazard is lowered to moderately severe and **slight** for Parleeville soils which are also common in this district and which have a comparatively low inherent erodibility.

Increased rainfall factor and stronger than average relief should enhance erosion in the southerly located Fundy Plateau and Fundy Coastal Ecodistricts of the Modal Forest. Fortunately, these districts are dominated by soils of the Lomond and Juniper Associations which have low inherent erodibilities. Data from a modal pedon of the Lomond Association indicates a PSL of 5 Mg ha^{-1} yr^{-1}.

It should be restated that above values for PSL were obtained under the assumption that the soil had been bared across the total area to its mineral horizons. This is rarely the case unless wood yards and landings or large cut and fill slopes along new roads are involved. On a regular clear-cut, most of the forest floor is retained and slash is deposited for additional protection. The task, crucial to a realistic projection of the erosion hazard, is to determine to **what degree the PSL materializes** under current methods of forest harvesting and regeneration in the region. It is the need to quantify C and P of the USLE. For bare soil, C is equal to 1. It reduces to 0.004 under grass cover and presumably approaches 0 under a continuous forest floor of minimal thickness (5 cm). Consequently, C must rise above 0 in proportion to the area of exposed mineral soil. Of further importance is whether or not the soil has been compacted on skid or porter trails, as this increases the inherent erodibility (K) of the soil, whether machine movement followed contour lines or occurred predominantly up and down slope (Fig. 4). Direction of machine movement and depth of soil disturbance are of equal importance in mechanical site preparation of clear-cuts for planting (Fi.5). These are conditions that may be expressed by the P factor.

Climate, geology and soil are generally **not conducive** to mass movement by debris avalanches, slumping and creep in the Fundy Model Forest area. Precipitation is well distributed throughout the year. With the possible exception of the snow melt period, prolonged water saturation and buoyant condition are not common in regional soils. The topography does not provide for excessive relief promoting debris avalanches. Most importantly is the abundance of coarse fragment and rapidly increasing bulk density with soil depth which provide for a high shear resistance and limit the buoyancy effect. Also, soils in the Appalachian region of Canada are generally low in smectite-type clay minerals (Kodama 1979) which promote slumping and creep. **Slope failure is thus uncommon in the region.** However, slumping may occur at some level of probability in silt loam soils and basal till on mid and lower slopes after clear-cutting of tolerant hardwoods, and would not be unusual on cut and fill slopes of new roads.

Preventive and mitigating measures

The extensive research of the past decades has yielded numerous recommendations for controlling soil erosion and loss of water quality (e.g. Haupt and Kidd 1965; Rothwell 1978; Megahan 1981). These are expressed today as BMPs for use in many jurisdictions (e.g. Cullen 1991; Maine Department of Conservation 1991; State of Washington Forest Practices Board 1992). BMPs were primarily aimed at the preservation of water quality and aquatic habitat. They were found to be effective for this purpose (Brynn and Clausen 1991; Phillips et al. 1994; Briggs et al. 1996) and may also have helped, where complied with by operators, to sustain the productivity of cut-over soils by reducing erosion. Minimizing the area affected by skidder and porter traffic should be first among guidelines for controlling erosion on clear-cuts. As observed by Rothwell (1978) a haphazard system of skid and truck roads can occupy 20% of the logged area whereas a well-planned system need occupy only 10%.

Critical to effective erosion control is the grade at which skidders and porters operate. Recommendations for trail location vary somewhat, but not widely with jurisdiction. For example, in New Hampshire, trail grades should be kept at 15% or less (Cullen 1991). In Maine, skidding is discouraged at grades >10% and over wide distances (>800 m). Directions further call for skidding across slopes, if safe, rather than straight down or uphill. For skid trails in steep terrain (slopes >10%) erosion control devices are identified such as drainage dips, skid humps, water bars and turnouts (Maine Department of Conservation 1992). Regulations from Washington State simply prohibit use of tractors and wheeled skidders on slopes where in the Department=s opinion damage to the resource could result (State of Washington Forest Practices Board 1991).

To further control erosion, existing BMPs require that yards and landings are established on gentle slopes with well drained soil, that water is diverted into adjacent areas protected by forest floor and slash, and that the soil is stabilized after closeout (mulching with logging slash, bark or straw, establishing grass cover). The latter also applies to terminal haul roads abandoned after the cut. Not surprisingly, erosion losses were found to be heaviest and of longest duration if the soil was left unstabilized after closeout of yards and landings (Briggs et al. 1996). Although mass erosion is not a common hazard, it would be prudent to restrict forest harvesting to selection cutting and to exercise extra care in road construction where slumping is probable.

It is not intended to present a complete set of preventive and mitigating measures for soil erosion in this discussion. Such exist in the references cited above and other documents. A broad collection of BMPs from the published literature has previously been presented for consideration in the Fundy Model Forest (Jewett 1995), but it should be recalled that BMPs were defined primarily for preserving aquatic systems. There may be a need for revision and supplementation if erosion is to be controlled effectively and soil quality preserved under prevailing forestry practices and at all levels of environmental constraints.

Monitoring soil erosion

Defining and verifying the validity of BMPs for erosion control will require periodic determination of actual soil loss and displacement. The information can be obtained in soil disturbance surveys as suggested under soil compaction. Criteria for field tallying should be chosen in such a way that semi-quantitative estimates of erosion can be made on an area with forestry activities, and comparison among sites are possible. In the simplest form, a surveyor notes the absence or presence of denudation or deposition at each point of observation, and estimates the level of each of these processes at each observation point.

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