Logging and Mass Wasting in the Pacific Northwest with Application to the Queen Charlotte Islands, B.C.: A Literature Review

Land Management
REPORT NUMBER 53

ISSN 0702-9861

December 1987

Ministry of Forests
and Lands

FISH/FORESTRY INTERACTION PROGRAM

This study was undertaken as part of the Fish/Forestry Interaction Program (FFIP), a multidisciplinary research study initiated in 1981. The program was started following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands forest land base. Originating on steep slopes, many slides deposited tonnes of debris in streams and on valley flats. The events raised private and public concerns over logging practices on the Islands and prompted the establishment of the 5-year program. Overall objectives of FFIP were:

- to study the extent and severity of mass wasting and to assess its impacts on fish habitat and forest sites.
- to investigate the feasibility of rehabilitating stream and forest sites damaged by landslides.
- to assess alternative silvicultural treatments for maintaining the improving slope stability.
- to investigate the feasibility and success of using alternative logging methods, including skylines and helicopters, and by logging planning to reduce logging-related failures.

The program is jointly funded by direct appropriations from the Canada Department of Fisheries and Oceans, the B.C. Ministry of Forests and Lands (Research Branch), and the B.C. Ministry of Environment and Parks (Fisheries Branch). Participating agencies include the Canadian Forestry Service (Pacific Forestry Centre), and the Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C.

Program results are published through the B.C. Ministry of Forests and Lands, Land Management Report series, as well as in papers presented at symposiums, conferences, and through technical journals.

For information about the program contact Ministry of Forests and Lands, Research Branch, 1450 Government Street, Victoria, B.C. V8W 3E7.

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December 1987

FERIC Special Report Number SR-45

Ministry of Forests
and Lands

Canadian Cataloguing in Publication Data

Sauder, E. A.
Logging and mass wasting in the Pacific Northwest with application to the Queen Charlotte Islands, B.C.

(Land management report, ISSN 0702-9861 ; no. 53)
(FERIC special report ; no. SR-45)
Issued jointly with Forest Engineering Research Institute of Canada.

Bibliography: p.
ISBN 0-7718-8606-3

1. Logging - Environmental aspects - British Columbia - Queen Charlotte Islands. 2. Mass-Wasting - Environmental aspects - British Columbia - Queen Charlotte Islands. 3. Forest soils - British Columbia - Queen Charlotte Islands. 4. Logging - British Columbia - Queen Charlotte Islands. I. Krag, R. K. II. Wellburn, G. V. (G. Vernon) III. British Columbia. Ministry of Forests and Lands. IV. Forest Engineering Research Institute of Canada. V. Title. VI. Series. VII. Series: Special report (Forest Engineering Research Institute of Canada) ; no. SR-45.

SD387.E58S27 1987 634.9'82 C87-092187-8

Published by the
Information Services Branch
Minstry of Forests and Lands
Parliament Buildings
Victoria, B.C.
V8W 3E7

Copies of this and other Forests and Lands titles are available at a cost-recovery price from the Queen's Printer Publications, Parliament Buildings, Victoria, B.C. V8V 4R6

ABSTRACT

This report is a review of available information on the influence of yarding systems on erosional processes in the Pacific Northwest and the Queen Charlotte Islands. Literature was reviewed and the relevance of these studies to forest harvesting on the Queen Charlotte Islands is discussed, and discussions with local Queen Charlotte Islands' forest company and agency staff are incorporated. Yarding systems that were considered potentially effective in reducing mass wasting are also noted.

ACKNOWLEDGEMENTS

The authors are grateful to the following people for their timely review and comments on this report:

- Eric Bentsen, Gerry Young, Don Hoffman, and Gilbert Brennenstuhl-Crown Forest Industries Ltd.;
- Jim Connors and Paul Chapman-MacMillan Bloedel Ltd.;
- Harvey Hurd, Phil Wainwright, Trevor Boniface, and Ron Bronstein-Western Forest Products Ltd.;
- Bill Bourgeois and Terry Rollerson-Woodland Services, MacMillan Bloedel Ltd.;
- John Williams and Kevin Orpen-Wedeene River Contracting Ltd.;
- Charles Mann and Bob McGaughey-U.S. Forest Service, Forestry Sciences Laboratory, Seattle, Washington;
- Doug Swanston-U.S. Forest Service, Forestry Sciences Laboratory, Juneau, Alaska;
- Dave Wilford, Jim Schwab, Terry Dyer, and Robert Laird-B.C. Ministry of Forests and Lands;
- Les Powell-Canada Dept. of Fisheries and Oceans;
- Vince Poulin-Fish/Forestry Interaction Program.

The authors are also grateful to the B.C. Ministry of Forests and Lands Communications staff for their detailed editorial review, and to Ella Kilde and Moya Whelan (FERIC) for their typing of the manuscript.

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1 INTRODUCTION

This is the first of four reports prepared by the Forest Engineering Research Institute of Canada (FERIC) as part of the prescriptive component of the Fish/Forestry Interaction Program (FFIP). It presents a summary of literature reviewed and discussions related to logging steep sites with Queen Charlotte Islands forest industry, Ministry of Forests and Lands (MOFL), Ministry of Environment and Parks (MOEP), and Canada Department of Fisheries and Oceans (DFO) staff. This report serves as an introduction to three separate studies that FERIC undertook. These studies examined landslides that occurred on logged areas (Krag *et al.* 1986), yarding systems (Sauder *et al*. (1987), and logging planning (Sauder *et al.* 1988).

The timber resources of the Queen Charlotte Islands (QCI) are important to Canada, British Columbia, and the local residents. The forest sites are extremely productive and Sitka spruce is one of the most valuable trees. Logging companies are the Islands' largest employers. The productive forest area on the Queen Charlotte Islands (736 668 ha) represents 1.8% of British Columbia's land base, and produces 3% (2 547 800 m^3) of the provincial annual cut.

The forest land is managed by companies under Tree Farm Licence (TFL) agreements (total annual cut 2.05 million m^3) and in a Timber Supply Area (TSA) by the Ministry of Forests and Lands (total annual cut 0.45 million m^3).

The need to examine the impacts of steep-slope logging arose because of landslides that occurred in the 1970s. In 1975-76, Alley and Thomson (1978) examined portions of the Queen Charlotte TSA near Davidson Inlet and Rennell Sound. They concluded that, as a result of extremely high rainfall, strong winds, rapid weathering, steep slopes, geologic character, and seismic activity, large portions of the timber lands were naturally unstable and geomorphically active. They recommended avoiding harvesting these slopes until studies were made to determine the consequence of the slides.

Two major storms triggered landslides throughout the Islands in the fall and winter of 1978-79. Landslides were particularly numerous and visible on logged areas and many of these deposited debris into stream channels. As a result, public and government agencies became concerned that logging-accelerated mass wasting was harmful to fish.

The first analysis (B.C. Ministry of Forests 1982) undertaken to determine the volume of timber available on a sustained yield basis for the Queen Charlotte Islands' TSA stated that 16 percent of the TSA area, or 63 800 ha, should be removed from the gross inventory as Environmental Protection Areas (EPA) largely due to soil instability. Half of the timber volume on an additional 5100 ha was also withdrawn because QCI management experience indicated specific areas of instability outside of the EPA boundaries. These additional withdrawals consisted of all timber on slopes greater than 35° (70%) and half of the timber on slopes between 25° and 35°. The report stated that an additional 45 000 m^3 per year of timber in the TSA may become available if logging systems are developed which permit harvesting without excessive environmental degradation. The Forest Engineering Research Institute of Canada was directed to investigate the potential of alternative logging systems to successfully harvest these unstable slopes as part of the Fish/Forestry Interaction Program (Poulin 1984).

The objectives of this report are threefold:

1) to review and discuss published studies that relate mass wasting to logging or yarding systems;

2) to describe alternative yarding methods for reducing the potential for mass wasting on the Queen Charlotte Islands' marginally stable terrain; and

3) to identify those yarding systems that might successfully provide access to timber in areas where logging has been deferred.

The impacts of actual and potential landslides on fish habitat or forest site loss are discussed in other FFIP reports.

2 EROSION PROCESSES AND FOREST SOILS ENGINEERING

The forest engineer proposing logging systems for steep, potentially unstable terrain must have a basic understanding of the erosion processes (surface erosion and mass wasting), soil mechanics, and the influence that geologic structure, soil engineering properties, hydrology, and vegetation have on basic slope stability.

2.1 Erosion and Mass Wasting

The general term erosion refers to the detachment and transport of soil materials from place to place. Specifically, surface erosion is the transport of individual soil particles by water and gravity, whereas mass wasting is the movement of large volumes of earth primarily under the influence of gravity. Swanston (1969) defines mass wasting as the "slow to rapid downslope movement of large masses of earth material of varying water content, primarily under the force of gravity". Landslides, slope movements, slope failures, and failures are used interchangeably throughout our reports.

Slope movements are the dominant geomorphic process throughout the mountainous regions of the North American west coast. This is a result of steep slopes, high rainfall, strong winds, recent geological and glacial activity, and continued seismic activity (Swanston 1969; Swanston and Swanson 1976; Alley and Thomson 1978; Wilford and Schwab 1982). Surface erosion processes (sheet wash, freeze-thaw, and rilling) are of secondary importance (Swanston 1976; Geppert and Larson 1984; Montgomery 1976; Megahan 1976) and are usually associated with forest roads.

While direct linkages between surface erosion and mass wasting have not been documented in the literature, indirect linkages have been proposed by Sidle (1980a), Cromack *et al.* (1979), and Swanson and Fredriksen (1982) because eroded material may be deposited in upland depressions where it could be susceptible to further surface erosion or slope movement. Another indirect link is that rainfall intensity, slope, soil structure, removal of vegetation, and the exposure of mineral soil are the basic factors influencing both surface erosion and mass wasting.

Rice (1979) proposed that the severity of surface erosion and mass wasting erosional processes depends upon the silvicultural system, the type of yarding equipment, soil texture, geology, and, above all, the topographic features of the area.

Slope movements have been classified by their type of movement and the type of material (Varnes 1978). The slope movements most often associated with forests and forest harvesting practices on the Pacific coast (Swanston 1969, 1971; Alley and Thomson 1978; Varnes 1978; Wilford and Schwab 1982) were:

- debris slides-shallow failures of unsaturated, relatively unconsolidated soils and logging or forest debris by a sliding or rolling action;
- debris flows - shallow failures of water-saturated soil and debris, by a true flow process;
- debris torrents - special type of debris flows that occur in steep walled V-notch gullies.

Three other types of failures that have been identified on the Queen Charlotte Islands, but are seldom associated with logging and do not appear to seriously impact fish habitat, are:

- rock falls - rapid slope movement by free falling (usually through air or by bouncing) of individual particles or masses of rock detached from bedrock;
- creep or slump earthflows - deep-seated failures that initiate as rotational slumps in saturated soils and move very slowly downslope as flows;
- dry ravel - the sliding or rolling of individual particles or aggregates of cohesionless materials on steep, sparsely vegetated slopes. Swanston (1971) states that this is a dominant process in southern California. The occurrence of talus-like slopes at the base of non-vegetated steep gully walls in the Queen Charlottes suggests that a similar process occurs there.

These three latter failure types were not considered in any detail in our studies.

Swanston (1974a) described two general failure mechanisms that occur in the western United States and that are applicable to the Charlottes. Translational sliding occurs when a soil unit initially fails along a relatively smooth inclined surface. Rotational failure occurs when a soil unit fails initially along an upper concave surface by outward rotation. A bare spoon- or wedge-shaped slide scarp results from either failure mechanism.

Following initial failure, the upper oversteepened, exposed soil mass may fail again and add material to the debris accumulation below. Deitrich *et al.* (1982) suggest this progressive infilling of landslide scars, depressions, and gullies can lead to soil wedges of deeper depths than the surrounding terrain over a period of 1000 - 10 000 years.

2.2 Principles of Soil Mechanics

A soil or rock mass that forms part of a slope has a gravitational force or shear stress compelling it downslope, and a combination of cohesion, friction, and root strength (collectively known as shear strength) holding the soil unit in place (Figure 1). To assess slope stability, these forces are analyzed as they act on a potentially failing mass. When the shear stress equals or exceeds shear strength, failure occurs.

Only the fundamentals of the infinite slope stability analysis have been reviewed. Further details on analysis and explanations can be obtained from Bishop and Stevens (1964), Swanston (1970, 1971), Wu (1976), Schuster and Krizek (1978), Sidle and Swanston (1982), and Sidle *et al.* (1985).

2.3 Factors Which Affect Soil Stability

"Single factors can seldom be attributed to the initiation of a landslide and often the final factor may only be a trigger that sets in motion an earth mass already on the verge of failure" (Sowers and Sowers 1951, cited by Bishop and Stevens 1964). Examining the factors that contribute to slope instability by influencing shear stress and shear strength provides a basis for understanding how different types of yarding or logging disturbance may influence slope stability.

Soils are classified as cohesive or non-cohesive. Cohesive soils are fine grained, have a high clay content, and are considered plastic. Non-cohesive soils are coarse textured or granular, and are considered non-plastic. The basic factors that influence slope stability (summarized by Sidle *et al.* 1985) for all soils on slopes susceptible to slope movements are: pore water pressure; soil strength parameters; slope-steepness; and depth of soil above the failure surface. These factors influence cohesive and non-cohesive soil stability in different ways.

In 1976, the B.C. Environmental and Land Use Committee (B.C.Ministry of Environment 1976) introduced a terrain classification system based on the character of surficial deposits by their genetic material. Other organizations - MacMillan Bloedel Ltd., the B.C. Ministry of Forests and Lands, and FERIC (Krag 1980) - used the classification as a basis for developing slope stability and hazard-rating systems that incorporate soil type, slope, soil moisture, aspect, and climate.

2.3.1 Factors affecting shear stress

The slope of a hillside and the potential failure plane is a result of geological, terrain and soil formation and glacial or stream modifications (Swanston 1971). While these factors will not change as a result of logging, a soil unit on a steep slope or within a soil wedge will have a greater shear stress compared to a similar unit on a gentler or adjacent slope. Slope also influences the effective mass of soil and must be considered along with the degree of bedrock weathering and climate (Sidle 1985; Sidle *et al.* 1985). Soil mass is the major factor influencing frictional resistance to sliding for non-cohesive soils (Klock 1979). The removal of downslope support of a soil unit is cited by Swanston (1974a) as increasing slope instability.

Timber removal reduces the weight acting on the soil mass and may provide a one-year period of stability on some areas (Brown and Sheu 1975). However, the downslope mass component is only a small part of the total soil mantle (Bishop and Stevens 1964; Ballard and Willington 1975; Klock 1979). Accumulations of felled trees may redistribute the weight acting on a soil mass; however, no references were found in the literature that this resulted in a landslide.

Swanston (1974a) suggested that dynamic loading on a soil mass can occur and temporarily increase shear stress when wind stress on trees is transferred through the root system to the soil. Although Swanston's comment was directed to forested terrain, dynamic loading could apply to exposed backspars along cutting boundaries, and may occur where wind forces are replaced by loads from logging equipment.

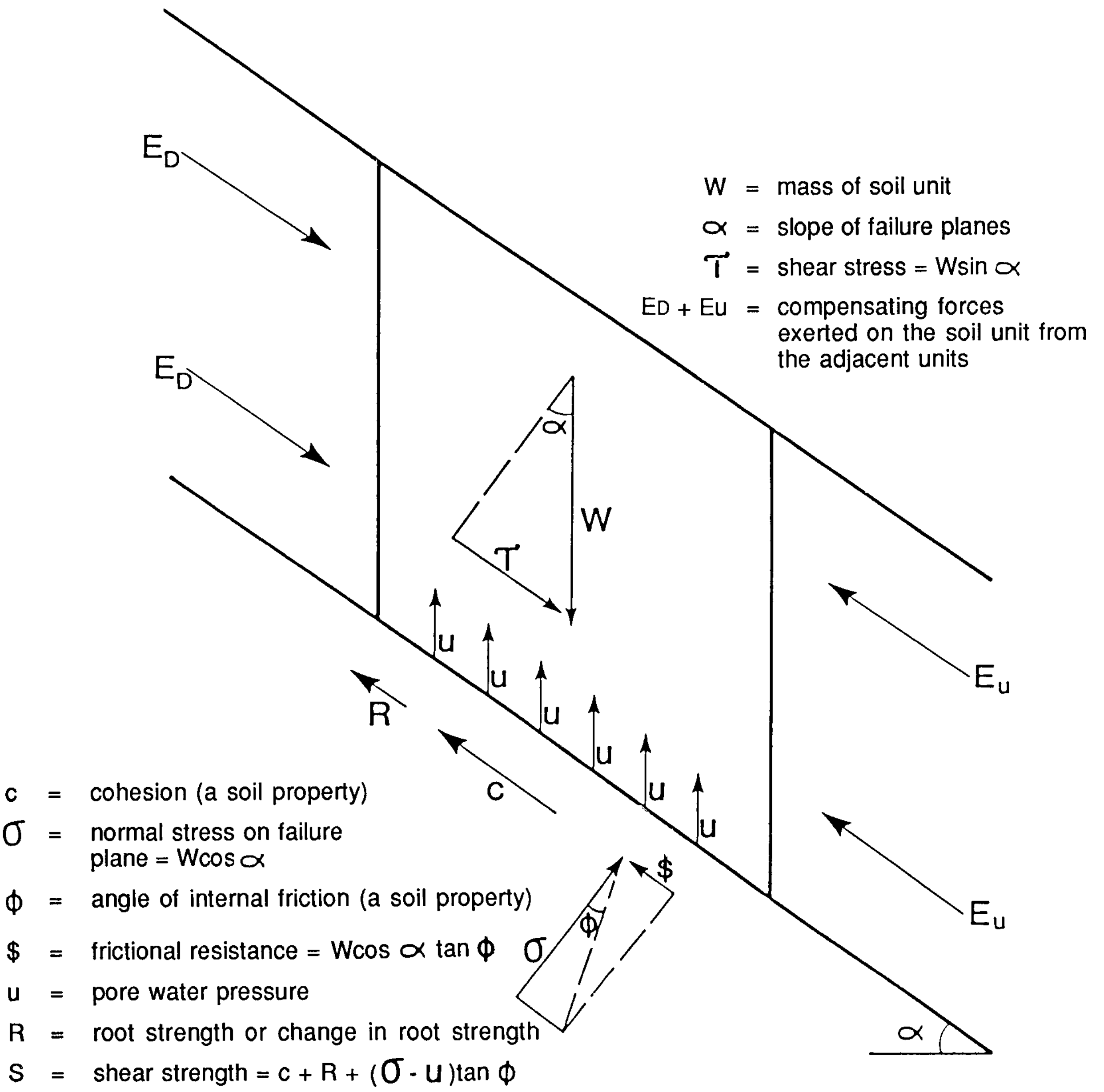

FIGURE 1. Simplified soil mechanics.

Klock (1979), discussing the engineering aspects of forest soils in the Douglas-fir region of the Pacific Northwest, stated that the rising pore water pressure from heavy precipitation could offset the effective mass of soil units on a slope by reducing the interlocking force between soil particles and result in an uplifting or buoyant force on the soil unit. He suggested soils on slopes in the region would have a greater degree of stability when the pore water pressure is falling, stable, or absent, compared to when the water table is rising.

Swanston (1969) pointed out the sensitive nature of consequent drainage channels that are a result of surface run-off following glacial retreat, and that dissect glacial till slopes in southeast Alaska. Soil-water seepage is concentrated along these depressions and surface flow only occurs when the underlying soil is saturated during periods of heavy rainfall. The presence of buried organic layers, organic lenses, and overturned soil profiles at the foot of such depressions indicates their history of failure.

The addition of water to soil can also increase the unit soil weight (Swanston 1970; Bishop and Stevens 1964). Stress to strength ratios are, however, unchanged provided the soil is not saturated (Bishop and Stevens 1964). Water comes from the precipitation, redirected surface flow, and disrupted subsurface flow. The scraping away of surface litter may disrupt the flow of subsurface water, and the exposure of mineral soil or uprooting of stumps may allow water direct access to deeper soil layers. Water may follow the macro channels left by roots when they were pulled out or increased in size by vibration during logging.

The presence of soil macropores (created by decayed root channels, drying cracks, small animal burrows, and interaggregate pore spaces) have been proposed by a number of researchers as being important to hillslope water movement (summarized in Sidle *et al.* 1985). Soil stability could increase as a result of water being directed away from potentially unstable soil units. Wilford and Schwab (1982) suggested that soil moisture flow through pipes was one of the main factors initiating mass movements in forested terrain surrounding Rennell Sound on the Queen Charlotte Islands. The disruption of the discontinuities in these macropore channels have been cited in the above references as initiating debris slides by increasing soil pore water pressure in soil units. Disturbance that could interrupt such macropore channels (dislocated stumps, gouging, and compaction) may therefore decrease the stability of a soil mass. Chamberlin (1972) suggested that subsurface stormflow in the form of interflow and deteriorating voids in soil structure as a result of vegetation removal and disintegration of roots could reduce soil stability.

2.3.2 Factors affecting shear strength

Shear strength of soils is determined by their physical properties and can be altered by weathering, changes to the intergranular forces, and changes in structure (Montgomery 1976). Shear strength can be decreased when the soil cohesion, the angle of internal friction, and the effective weight or normal stress of the soil mass are reduced.

Shallow soil mantles that overlie smooth bedrock surfaces, cemented hardpan, or clay layers on steep slopes provide ideal opportunities for translational failures in coastal British Columbia and elsewhere (O'Loughlin 1972; Swanston 1974b).

Swanston (1974b, 1978) noted that the underlying structure of bedrock or compacted glacial till (the degree of fracturing and faulting, and the orientation of bedding planes and joints) will influence the potential for the soil to anchor itself to the parent material. Thus, the geology, topography, and glacial history of coastal B.C. lends itself to frequent natural slope movements (Swanston 1978). Sidle (1985) noted that crystalline igneous and metamorphic rocks and competent sedimentary rocks may offer difficult anchoring for soil particles and that bedding and jointing planes, if they occur, may assist soil attachment to bedrock. However, Sidle also noted that clay layers located at the soil-bedrock interface could provide a suitable surface for failure.

The shape of the terrain can affect how subsurface water is distributed. Sidle (1985) suggested that convex shapes tended to disperse water and were therefore relatively stable. Concave slopes tended to concentrate water into localized areas, thereby increasing the susceptibility for failures.

The soil wedges located at infilled depressions and described by Dietrich *et al.* (1982), consist of a deeper soil with a higher proportion of organic material than on the adjacent slope. Depressions such as these concentrate and channel subsurface drainage. They are therefore prone to the development of temporary water tables, generation of high pore water pressure, and increasing shear stress (Swanston 1969).

Live tree and ground vegetation roots provide reinforcing strength to the soils on many of the steep, shallow-soiled coastal slopes (Bishop and Stevens 1964; Swanston 1970; O'Loughlin 1972; Burroughs and Thomas 1977; Ziemer and Swanston 1977). This reinforcing strength is probably the main stabilizing factor on the colluvial and morainal slopes. For soil mechanics analysis, root strength is assumed to augment the soil cohesive properties (Wu and Swanston 1980).

Roots reinforce and tie together the soil by providing: shear or tensile strength parallel to the bedrock surface; vertical anchoring through shallow soil depths (less than 1 m) to fractured bedrock; and lateral bridging between root masses as roots intertwine and "weld" together (Sidle 1985). On the Charlottes, the rooting depths are shallow and generally less than 1 m below the surface (Wilford and Schwab 1982). The shallow soils overlying bedrock on upper slopes and compact glacial till on lower slopes on the Queen Charlotte Islands suggest that lateral bridging (and to a lesser extent anchoring) may be important contributors to slope stability in this region. Logging removes the live tree root component. Yarding disturbance that displaces vegetation and uproots small trees and stumps further reduces the effect of the root network and decreases soil shear strength.

Increased weathering of bedrock or till surfaces may lead to reduced cohesion as calcium carbonate is leached, clay mineral structures are altered, and freeze-thaw of shallow soils occurs (Ryder 1983). Logging disturbance has not been shown to increase weathering.

3 TIMBER HARVESTING AND SLOPE STABILITY

Several studies in western North America and elsewhere have demonstrated that landslide frequencies are higher on logged areas than on similar forested areas. These studies provide information on the sources of slope failures as well as recommendations to reduce failures from logging, and relate failure frequencies to logging, systems, and practices. The studies generally do not identify specific mechanisms for failures occurring as a result of yarding.

In 1961, Bishop and Stevens (1964) studied landslides in two drainages in Maybeso Creek in southeast Alaska. They reported the number and area of slides increased by 4.5 times during the 10-year period since logging began. Factors that were associated with logging landslides were: heavy rainfall, steep slope, weak geologic and soil properties, and deterioration of root strength. Bishop and Stevens also noted the increased erosive power when logging slash and debris are transported in earthflows in V-notch gullies.

This pioneering study of Bishop and Stevens (1964) appears to have had a strong influence on the thinking of subsequent researchers and their interpretation of the relationship between highlead logging and mass wasting.

The first major inventory of landslides following a severe winter storm was undertaken by Dyrness (1967a) when he examined mass soil movements that occurred during the winter of 1964-65 in the H.J. Andrews Experimental Forest of central Oregon. He found that steep slopes underlain by soft, deeply weathered pyroclastic rocks were highly susceptible to mass wasting whether or not any disturbance occurred.

Dyrness found that there was a 10 times increase in failures within logged areas. Of the 47 failures examined, 34 were associated with roads. He suggested that slides could be reduced through the use of skylines and balloons, which require less road than highlead, and by improvements in road location.

Swanston (1969) concluded that steep slopes and excessive soil water were the principal causes of landslides in southeast Alaska. The upset of slope equilibrium by logging and the destruction of root systems by clearcutting were considered to be secondary factors. Swanston recommended avoiding the logging of slopes most susceptible to mass wasting. He suggested delineating areas of similar slope and establishing cutting patterns that would minimize disturbance on slopes that equalled or exceeded the natural angle of internal friction (34° or 70% slope).

Fredriksen (1970) examined three watersheds in the H.J. Andrews Experimental Forest in Oregon to determine the source and amount of sediment entering drainages. Two logging systems in different watersheds were compared to an undisturbed watershed. Twenty-five percent of one watershed was patch cut and highlead yarded to a road system which occupied 6% of the area. A second watershed was clearcut but had no roads. Logs were partially suspended to a fixed skyline, then downhill yarded fully suspended. Both areas were slashburned. Comparisons showed that during the period 1960-68, sediment in streams increased 109 times in the roaded patch cut area and 3.3 times in the skylined area. The roaded area had one landslide from a mid-slope road before logging and 32 slides during a storm after logging. Six of the largest slides resulted from roads. Only four slides occurred in the non-roaded area and none in the unlogged control area.

Fredriksen made three recommendations:

1. minimize disturbance from road construction;
2. reduce mid-slope roads by using skyline systems;
3. minimize disturbance to streams.

In 1971, Gonsior and Gardner (1971) examined an area in the Payette National Forest in Idaho. The area had been experimentally logged using tractors, jammers (small truck-mounted highlead yarders), and a skyline system. The major landslides on the area resulted from road construction. The authors recommended several road construction practices: avoiding unretained fills on slopes over 35° (70%); compacting fills and removing organic material (especially stumps); and improving the handling of surface water.

Megahan and Kidd (1972a) examined the effects of jammer and skyline logging over a 6-year one roadfill failure. Eighty-four percent of the total sediment yield increase for the 6-year period occurred in the first year. The authors concluded that erosion from roads could be reduced by careful road location, design, construction, and maintenance.

In the second part of the study, Megahan and Kidd (1972b) monitored sediment movement from jammer settings and a skyline logged area. They found no difference in surface erosion (excluding roads) between the two systems. They concluded that "the greatest benefit from skyline systems is the erosion reduction from reduced road mileage". This underscored the conclusion of Haupt and Kidd (1965) who said that skyline logging could alleviate sediment production although it might be unacceptable if roads are not properly constructed.

It is apparent from these studies that roads are the major source of landslides on logged steeplands. Therefore, yarding systems that require high road density have a greater potential to impact streams than logging systems requiring less road. The effects are compounded if roads are not properly located or built.

The first study in British Columbia of the effects of steep slope clearcut logging on soil stability was completed by O'Loughlin (1972). The study area was located in the Coastal Western Hemlock Biogeoclimatic Zone of the southwestern part of the province on the east side of Howe Sound. Logged areas were found to have 1.5 landslides per square kilometre, or a 7.5 times increase compared to non-logged areas. Of 49 landslides examined, 26 occured within drainage depressions, 14 on open slopes, 7 at road fill failures, and 2 at the cut-slope above a road. O'Loughlin noted that road construction appeared to be more detrimental to the stability of the coastal mountain slopes than other human activities. He also found that:

- long uniform slopes were more landslide prone than short, broken, stepped slopes with large amounts of exposed bedrock;
- mountainsides with slopes greater than 30° (58%) but less than 40° (84%) were most likely to suffer landslides.

O'Loughlin concluded that unstable road fills on steep slopes and the lack of drainage structures were the obvious causes of road-associated failures. It was his opinion that post-logging treatments such as water bars, outsloping, smoothing, and artificial revegetation may have prevented some landslides; however, these practices would have been ineffective on the very steep slopes that occur above 800-m elevation.

In a study in the Chilliwack Valley, Ballard and Willington (1975) used soil shear strength and stress equations to analyze the effects of various site conditions on slope instability. Cohesive soil strength, slope, root strengths, pore water pressure, soil texture, material deposition, organic material burial, and the unloading of the slope by timber removal were discussed as variables. The frictional angle for many of the surficial materials was found to be 37° (75%); however, failures were also noted on slopes of 50° (119%). Because these slopes are steeper than the angle of repose, Ballard and Willington concluded that steep slopes were probably inherently unstable regardless of logging activity, and that the steeper failures were likely related to a gradual decline in strength due to weathering. Roots growing through the shear plane would contribute to soil strength. Ballard and Willington suggested that root channels provided a means for water to be diverted through the upper soil matrix. This may have, in turn, led to saturation of the soil layer just above the shear plane, resulting in increased pore water pressures, and reduced soil shear. The decay of buried organic material was also suggested as a method to initiate failures on slopes of greater than 45° (100%), especially if the material had been contributing to the soil strength. Timber removal was predicted to have only a minor effect on soil stability and could be positive or negative.

Ballard and Willington associated slope failures with the following conditions in the Chilliwack Forest:

- poor natural consolidation of the local geologic materials;
- slopes of weathered bedrock, colluvium, and glacial till, or slopes that are above the natural angle of repose and have steeply sloping planes of weakness along bedrock and till;
- root system decay and delayed development of new root systems after logging;

- removal of toe-slope support by road cuts;
- hydrologic regime changes resulting from logging, such as:
  - interception and channelling of water by roads, culverts, and yarding pathways to areas that were not previously receiving areas;
  - the insloping of roads toward poorly drained areas, which may lead to the roadbed being saturated during wet periods;
  - material bulldozed into ephemeral streams during dry weather;

Ballard and Willington suggested that the outsloping of roads and/or construction of water bars would be more effective than maintaining culverts and ditches.

In summarizing the causes of logging-associated mass movements on forest lands in southeast Alaska, Swanston (1974b) concluded that timber cutting on very steep slopes was the most damaging operation and mass wasting was attributed to the decay of the root matrix combined with heavy precipitation. Swanston also suggested that slash accumulations in deep V-notch gullies were a major initiating factor for gully failures. Road construction was not a major factor because at that time few roads in southeast Alaska had been built on unstable sites.

Swanston proposed two options for logging following the identification of unstable terrain: avoidance of any activity on such terrain and controlling the effects of logging. The latter option may be expensive and only partially successful, but there are several practical measures available for reducing surface disturbance, including: use of balloon or helicopter systems; improved road construction and maintenance; and use of selective harvesting and planting to maintain effective root strength.

Whereas Dyrness (1967a) looked at failures that occurred as a result of a single winter season, Swanson and Dyrness (1975) studied mass movements in the H.J. Andrews Experimental Forest that have occurred since the first road construction and logging activities began in 1950. In areas classified as unstable, a total of 139 failures were enumerated. Of these, 32 failures (46 600 m^3) occurred in unlogged forest areas, 36 failures (48 400 m^3) in clearcut units, and 71 failures (98 200 m^3) on road rights-of-way. The volume of landslide material eroded from roads per square kilometre of road surface was 30 times that on undisturbed forested sites and 10 times that of clearcut areas. Compared to the forested areas where 1.5 failures per square kilometre were recorded, there was a 23-times increase in failures within logged areas and a 31-times increase in failures associated with roads. Dyrness noted a 3-times and a 10-times increase in failures associated with clearcuts and road rights-of-way, respectively, after a single winter period. The slide history indicated that the effects of vegetation removal and road construction on landslide erosion may be reduced after 10-20 years.

Megahan *et al.* (1978) studied all landslide activity that had occurred in the Boise and Clearwater National Forests, Idaho, from 1973 to 1976. The effects of geology, landform, climate, and disturbances were noted. Road construction accounted for 58% of the landslides in the region. Landslides associated with logging and/or fire in combination with roads accounted for an additional 30% of the landslides. Timber removal alone contributed to 9% of the total. Only 3% of the landslides occurred on unlogged forested land.

Megahan *et al.* (1978) found that, as road standards increased, the volume of material to be excavated also increased. Slide density approximately doubled for each step in the road standard above the lowest standard (2 failures per kilometre). It was also noted that, when tree crown cover was below 80%, landslide occurrence appeared to be more sensitive to reduction in the shrub layer rather than tree crown layer. Landslides occurred most frequently 4-20 years after logging.

In another study to assess the relationship of logging to mass wasting, Gresswell *et al.* (1979) examined failures occurring as a result of a November-December 1975 storm in the Siuslaw National Forest, Oregon. Of particular interest in this study is the reduced volume of debris and frequency of landslides (compared to other studies) associated with roads. Of the 245 failures studied, 9% occurred on forested unlogged areas, 14% within road rights-of-way, and 77% within cutover areas. Road-associated failures produced 33% of the volume of slide debris occurring within logging areas; however, the average volume of debris was 0.7 times that of natural failures and approximately twice that of failures within clearcuts. Drainage-initiated failures accounted for 47% of the road failures.

Gresswell *et al.* (1979) attributed the reduction of road-associated failures to improved road design and construction techniques and the implementation of road, maintenance, and culvert and ditch cleaning patrols during storms. Nearly 50% of the clearcut failures occurred in the midslope position as a result of saturated soil conditions due to upper slope drainage, and nearly 33% of the failures occurred adjacent to streams, probably as a result of undercutting during storm flow or debris torrent activity. Two-thirds of clearcut failures occurred less than 4 years after harvesting.

In a literature review, Sidle (1980a) states that of all forest practices, road construction is the greatest source of surface eroded material. Based on his work, he suggested watershed protection must include: advanced planning of road systems; minimal road lengths and widths; the reduction of the number of steep grades; and the use of ridge-top road locations. Sidle felt skyline systems were effective in minimizing soil disturbance and compaction on very steep sensitive sites, since logs are either partially or totally suspended above the soil surface during much of the yarding process. In addition, he concluded that, to minimize surface erosion, uphill yarding was desirable to prevent cable roads from converging at a single point and thereby concentrating run-off water.

Sidle (1980b) reviewed the basic causes of mass wasting in Washington, Oregon, and Idaho, and discussed how clearcutting and road construction may affect them. Shallow failures were associated with roads and clearcutting. The alteration of groundwater flow was associated with the initiation of slumps and earthflows. The residue from harvesting operations could initiate debris torrents by overloading wet depression areas or by breaking up debris masses in gullies during rainstorms. Removal of the debris during yarding may reduce such failures.

A study of landslides that occurred as a result of a 1978 storm in the Rennell Sound area indicated that logging-associated landslide frequency accelerated four years after timber felling (Wilford and Schwab 1982). Roads were a major factor in initiating failures; however, Schwab noted that the number and area of clearcut failures was much greater when overall areas were considered. Root strength deterioration was the major factor associated with clearcut failures.

4 TIMBER HARVESTING AND SOIL DISTURBANCE

A major area of research has been directed at identifying and quantifying the effects of different yarding systems on soils. This has primarily resulted from concerns over the potential damage to the soil by ground skidding systems operating on steep slopes, and increased rates of surface erosion. Ground skidding, highlead and skyline cable systems, and balloon and helicopter yarding systems have been evaluated for the degree of soil disturbance associated with their operation.

Disturbance has been measured by classifying the depth of soil disturbed, measuring the amount of soil compaction, and determining the amount and distribution of logging slash. These measurements show how disturbance varies between different logging systems. However, the studies do not identify the specific role severity and type of disturbance have on initiating mass wasting.

Table 1 summarizes the findings of studies that have examined disturbance levels of various yarding and skidding systems. To our knowledge, researchers have not followed-up the disturbance studies to determine the longer-term relationships between disturbance, erosion, mass wasting, and site productivity. Intuitively, one would expect that when steep slopes are logged, the greater the amount of disturbance or the greater the severity of disturbance, the greater the potential for a slope failure to occur.

Roads have also been shown to initiate landslides, and several studies that estimate the road requirements for different yarding systems are presented in Table 2. The table shows that:

- ground skidding required more road than cable yarding;
- the use of a mobile spar road with the running skyline system increases the roaded area;
- the long-line skyline and a helicopter working with a skidding tractor can result in reduced road areas.

Several studies have looked at the effects of yarding over a snowpack (with tractor, highlead, and grapple) and of slashburning settings. Neither of these practices is applicable for logging slopes on the Queen Charlotte Islands since snowpacks occur infrequently and slashburning is not a standard practice.

Rice (1979) has used the extent of soil disturbance as an indicator of the effects of logging on forest sites. He suggests that while surface disturbance cannot be directly linked to erosion, the data is useful for establishing the relative impacts of different yarding systems to the site. In many studies (Smith and Wass 1976; Cromack *et al.* 1979; Cummins 1982), it was pointed out that some forms of shallow disturbance are beneficial and provide good growing sites for natural or planted regeneration. In addition, researchers commented on terrain or operational factors that are related to disturbance creation and the potential effects of the disturbance on the site.

Dyrness examined soil surface conditions following tractor and highlead yarding (1965), skyline yarding (1967b) and balloon logging (1972). The studies were carried out on steep slopes generally favourable to the particular yarding system, and on similar soils. Dyrness (1965) reported that highlead yarding roads were frequently protected by litter and scattered slash that reduced compaction. He also felt surface disturbance of the organic litter layer caused by the dragging of logs was important because the structure of the upper soil layer may be altered beyond that measured by bulk density. These unmeasured changes were thought to be potentially inportant to slope stability. In addition, Dyrness stated that, although the total cutting area was relatively undisturbed, areas with potential to initiate failure usually occupy only parts of the setting.

Dyrness (1967b) noted that the amount of shallow disturbance associated with the Wyssen Skyline Crane system was greater than highlead, probably as a result of the very broken, gullied terrain in his sample area that prevented full suspension of logs over the entire yarding distance. The major advantage of the Wyssen was that it reduced the number of roads required to access landings, compared to highlead.

During the balloon yarding study, Dyrness (1972) reported that tree falling caused most of the slightly disturbed areas and he felt this might have been reduced if precautions had been taken during felling. He also said that balloon yarding virtually eliminated gouging, dragging, and other log/soil contact during yarding.

TABLE 1. Summary of soil disturbance by yarding system

Author	Date	Area	System	% of Total Clearcut Area: Litter dist.	Shallow	Deep	Compacted	% of Surface Covered With Slash: Heavy	Light
1. Dyrness	1965	Oregon	Tractor		26.0	9.0	27.0	25.0	43.0
			Highlead		21.0	10.0	9.0	27.0	38.0
2. Dyrness	1967b	Oregon	Standing Skyline		24.0	5.0	3.0	11.0	54.0
3. Dyrness	1972	Oregon	Balloon		16.0	3.0	2.0	20.0	53.0
4. Bockheim *et al.*	1975	SW B.C.	Tractor	18.0	11.0	58.0		35.0	
			Highlead	30.0	18.0	11.0		41.0	
			Helicopter	31.0	2.0	3.0		45.0	
5. Smith and Wass	1976	Nelson, B.C. (unburned) (exclusive of roads)	Highlead (summer)	5.0	5.2	3.4		44.0	
			Grapple (summer)	12.6	2.5	0		52.0	
			Skyline (summer)	5.7	7.3	1.3		50.0	
6. Klock	1975	Washington	Highlead		44.5	32.0			
			Skyline		22.4	2.8			
			Helicopter		11.3	0.7			
			Tractor (summer)		37.6	36.2			
7. Schwab and Watt	1981	Cariboo, B.C.	Running Skyline		8.4	3.1			
			Tractor		16.3	27.8			
8. Clayton	1981	Idaho	Helicopter		17.0	2.0		82 (following first survey)-unburned	

TABLE 2. Summary of area occupied by roads

Author	Date	System	% of Site				
			Main	Perimeter/ Tailhold	Spur	Landing	Total
Schwab and Watt	1981	Running skyline	8.0	4.3		1.2	13.5
		Crawler tractor	5.6	2.7		2.3	10.6
Smith and Wass	1976 (unburned)	Summer highlead	6.6			2.0	8.6
		Summer grapple		27.1			27.1
		Summer Wyssen	0.0				0.0
		Summer ground skidding	7.6			0.7	8.3
Klock	1975	Helicopter & tractor	2.7		1.4	0.4	4.5
		Helicopter & tractor	2.8		2.1	0.4	5.3
		Cable & tractor	2.8		14.1		16.9

When Dyrness (1967a) examined the failures that occurred in the H.J. Andrews Experimental Forest, he noted that eight occurred in logged areas. He found it impossible to attribute logging to their initiation, but did feel that one or two would have occurred even if the area had not been logged. Dyrness suggested that logging could cause some small and insignificant changes to the slope that could be sufficient to upset the stability of the hillslopes.

Five postfire salvage logging systems (helicopter, tractor skidding, jammer, highlead, and a Wyssen skyline) were examined in a north central Washington study to compare the impact of harvesting systems on soil and vegetation (Klock 1975). Klock noted that surface erosion following logging was present on 3.4% of the helicopter logged area, and 41.1% of the highlead logged area. Erosion on the helicopter area was caused by overland flow on a steep sideslope. Klock felt that more severe soil disturbance by jammer and highlead skidding was reported in this study because the understory vegetation and forest floor litter had been destroyed by fire and was not present to protect the shallow unstable soil from the skidding of logs. Soil disturbance levels may have increased, according to Klock, because there was insufficient deflection for the highlead system to lift logs, and volumes of timber removed per acre varied with each harvesting system.

When summarizing the effects of logging on slope stability in Alaska, Swanston (1974b) noted that only small triggers were needed to initiate slope failures when the internal soil strength was reduced to a nominal value as a result of high rainfall. He suggested that root structures provide the primary strength in soils where geologic conditions cannot prevent soil movement, and that the direct destruction of these stabilizing roots by logging activity could initiate failure. In addition, Swanston noted that if roots were weakened, the direct effect of pore-water pressure could initiate failure.

Ballard and Willington (1975) felt the greatest effect on the slope stability due to logging was the diversion or channelling of water by roads, ditches, culverts, and yarding roads to areas that were never before receiving areas for such volumes.

Soil disturbance associated with tractor, highlead, and helicopter logging systems in southwestern British Columbia was examined by Bockheim *et al.* (1975). They observed that "the nature and degree of soil disturbance is neither uniform nor randomly distributed across a harvested area and a mosaic of disturbance intensity therefore results." The major factor influencing mineral soil exposure on highlead settings appeared to be slope angle. The greatest mineral soil exposure occurred on shale-derived slopes of greater than 35° (70%) and extreme disturbance of unconsolidated soil material occurred on slopes greater than 37° (75%).

Smith and Wass (1976) studied the effects of various types of clearcut logging in the Nelson Forest Region of B.C. -- ground skidding (summer and winter logged, burned and unburned); highlead and grapple (summer and winter logged, burned and unburned); and a Wyssen skyline (summer logged) -- on soil disturbance, vegetative cover, and regeneration. There were no roads within the Wyssen logged area. Between yarding roads for all systems, there was a higher proportion of shallow compared to very deep disturbance. Gouging by log butts, overturning of roots and the scraping of the base of stumps by dragged logs resulted in erosion and deposition. Serious erosion potential did not appear to exist within clearcut areas. Larger-scale erosion events that resulted in gullying and slides were mainly associated with drainage problems on roads and with particularly erosion-prone soil types.

Schwab and Watt (1981) surveyed running skyline yarded clearcuts and crawler tractor logged clearcuts in the Quesnel area of British Columbia. The authors concluded that the running skyline system better protected the soil resource than did tractor logging and that the running skyline system should be encouraged on marginally stable terrain.

Clayton (1981) undertook a study to evaluate the soil disturbance resulting from clearcutting and helicopter logging in a watershed. Helicopter logging and slashburning accelerated surface erosion on 2% of the area. Compared to pre-logging erosion, there was a 10-times increase in volume of material eroded over the short term.

Froehlich (1980) reviewed logging studies to 1977 that documented the effect of various logging systems on the environment. He concluded that:

- the amount of logging road may not be as important as the quality of construction;
- soil disturbance depends on slope, slope configuration, and the size and volume of timber being logged;
- most soil compaction caused by skyline yarding is concentrated around the landing;
- skylines can reduce logging impacts on stream channels by using full suspension, provided there are good layout and operation procedures.

To determine how log lead (the angle between the yarded log and the ground) affects the soil, Cummins (1982) experimented with small yarding models to simulate field conditions. He classified disturbance occurring from cable yarding as plowing and rutting. Plowing resulted when material was pushed aside as the log was dragged flat over the ground. Rutting (or gouging) was produced primarily by pressure and "squeeze-out" which resulted in compaction when one end of the log was dragged over the ground (Figure 2).

Cummins has modelled different log lead angles on different slopes and has recorded the depth of groove; whether the disturbance is plowing or rutting; the forces required to move a test log at various speeds; and the changes in the soil profile. Much of his research has shown that the proposed guidelines, which require one end of a log to be suspended, can actually increase the depth of disturbance (as the lead angle increases to a maximum when full suspension is reached). More favourable leads for minimizing disturbance occur when the log lead angle is just sufficient to clear stumps and obstacles. The maintenance of a 4° lead angle was shown to provide lift to the leading end of the log. Cummins proposed a system whereby forest engineers could check this angle progressively, as they worked out from the yarder.

Wilford and Schwab (1982) described the characteristics of failures and the factors leading to the initiation of mass wasting in the Rennell Sound area of the Queen Charlotte Islands. They concluded the main factors leading to mass movements on the logged areas were root decay, debris accumulation in gullies, yarding disturbance, alteration of surface runoff, weathering of surficial material and bedrock, root web weakening by yarding disturbance, and dynamic loading on timber exposed along the cutting boundary.

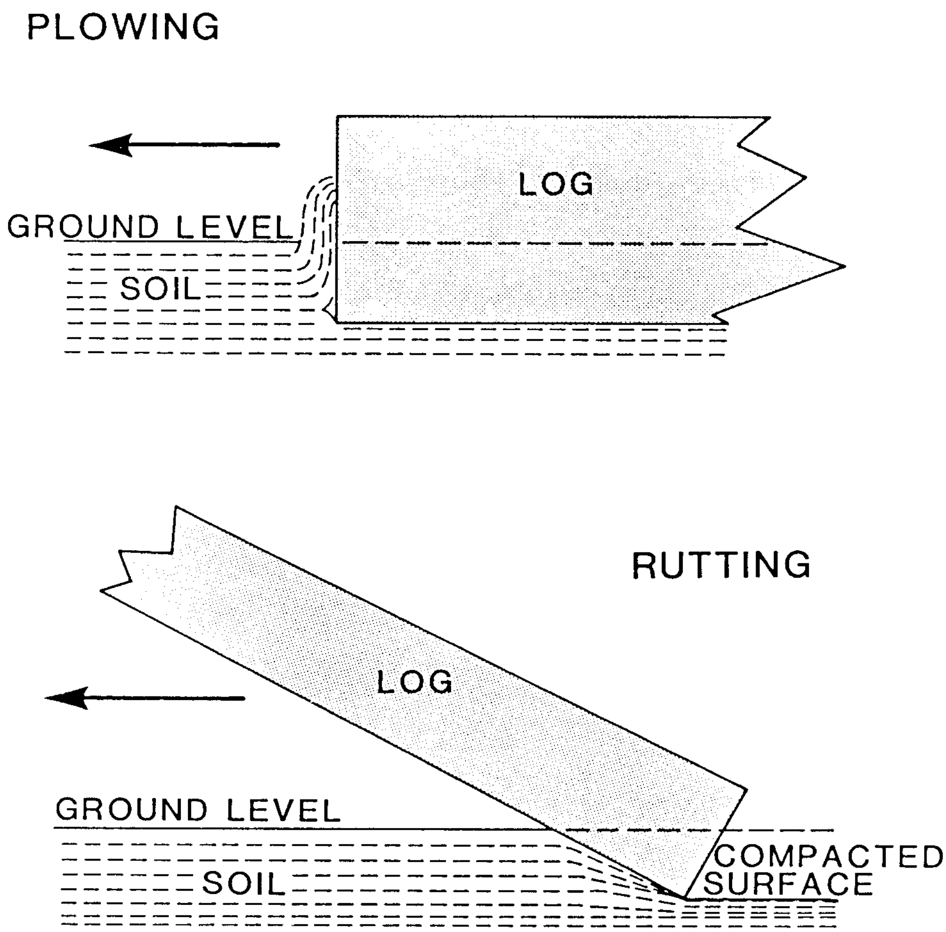

FIGURE 2. Plowing and rutting (Cummins 1982).

5 REVIEW OF CABLE YARDING SYSTEMS AND THEIR POTENTIAL TO REDUCE MASS WASTING

Researchers have favoured the use of skylines and helicopters to reduce mass wasting because these systems theoretically have longer yarding distance capability. Therefore, fewer roads and landings are required compared to conventional highlead yarding on this basis. The systems having the most potential for reducing slope movements are skylines, running skylines, long-distance skylines, and aerial systems such as balloons and helicopters.

Only aerial systems lift the logs from the ground and carry them fully suspended to the landing. Cable systems will always drag the log, even if it is only to the skyline.

Since many failures are associated with roads, systems able to reduce road distances will decrease the potential for slope movement. While it is important to avoid roads if they are not needed, Johnston (1974) pointed out that the future management implications of a roadless area for silvicultural work (tree planting, juvenile spacing, management surveys, and protection) must also be evaluated. A network of narrower roads could be implemented to provide access for light vehicle traffic providing their design standard, location, construction, and maintenance are undertaken carefully. If they are not, similar problems as result from conventional roads on steep terrain will occur.

Apart from system selection, the planning of yarding layout areas is critical if slope disturbances are to be reduced. Lysons (1974) felt that many logging problems (environmental and technical) of the past were more related to layout and application than to equipment design. Studier (1974) pointed out the importance of deflection and ground clearance in operation design, the need to have landings located in places where there is favourable lead to the tailholds and an adequate area to deck logs, and consideration of the future logging of adjacent timber. Aulerich (1974) stated that "layout of the yarding area is critical and has a direct bearing on the success or failure of the operation." Sauder and Nagy (1977) and Cottell *et al.* (1980) concluded that highlead yarding should not be given automatic preference when yarding layouts are designed. Reducing road lengths and landings through the use of running skylines, balloons, or heavy-lift vehicles, may reduce overall yarding system costs.

Slope movements can be reduced if yarding operations are planned:

- to reduce the amount of midslope truck road constructed on marginally stable slopes;
- to distribute yarding roads over a large area, preventing overuse of individual roads that could result in deep and concentrated soil disturbances;
- to locate yarding roads where the best lift is available or where disturbance will have minor effects;
- to clean up yarding debris from gullies and leave natural large organic debris in place;
- to clean up debris from landings.

The U.S. Forest Service has examined the following three logging systems that may be applied to areas sensitive to road and soil disturbance. Binkley (1965) studied the design, economics and operation of a radio-controlled skyline carriage used to log a sensitive unstable area in coastal Oregon. Total road construction was reduced when yarding distances of 360-2100 m were used.

Largely as a result of concern with the stability of a logging balloon during winds, the U.S. Forest Service studied a "natural shaped" logging balloon (Binkley and Carson 1968). It was found to be safe for logging operations in areas near the Oregon coast and was able to survive storms when properly bedded down.

Burke (1972) examined a mobile yarding crane (grapple) system and found that it could yard uphill or downhill with less soil disturbance than highlead yarding because the front end of the log was lifted off the ground. Full suspension of logs was also possible, provided there was adequate clearance from the ground to the tightened skyline. The heavy yarder required by this system, however, required stronger bridges and firmer road surfaces than highlead yarding.

5.1 Cable Yarding System

The skylines described below refer mainly to live skyline systems that require a mobile spar and yarder. All cable systems require sufficient deflection for logs to be inhauled without digging into the ground or stumps, firm tailholds for guyline, skyline, and running line anchors, and a place to deck logs.

5.1.1 Gravity skylines

A conventional highlead yarder can be adapted to a gravity or shotgun skyline system by simple modification (Conway 1976; Sauder 1978). The system will only work for yarding uphill; therefore, roads and landings must be located along the midslope to take advantage of concave-shaped areas at the base of long slopes or to provide access to ridges. A minimum slope of 30% between the top of the yarder and skyline tailhold is recommended to ensure the carriage "runs" to the tailhold. Yarding road widths are twice the length of chokers used. The system may reduce ground disturbance on steep uphill-yarded slopes by keeping one end of the log raised (and full suspension for limited distances), provided there is adequate clearance. A shortcoming of the system is the requirement for a midslope road to access landings.

5.1.2 North Bend and slackline system

A yarder with three operating drums is required for North Bend or slackline yarding. Uphill or downhill yarding is possible. Full suspension of the loads can be accomplished provided there is sufficient ground clearance. The North Bend system is particularly suited to yarding logs out of gullies or around obstacles. The skyline can be placed in an optimal location for deflection and ground clearance. Logs are laterally yarded further to the skyline with North Bend yarding, compared to slacklining. Both systems may reduce mass wasting by: providing partial or full suspension of loads; not requiring yarding roads to pass directly over sensitive sites; and reducing road development. Both of these systems direct logs from a large area over a single yarding road where soil disturbance and gouging may occur.

5.1.3 Running skylines

A yarding crane (a yarder mounted on a swing-type undercarriage and using the running skyline system) has potential to reduce the size of landings on steep slopes and yarding disturbance. The swing ability reduces the need for large landings, as the logs can be pulled onto the road or piled up beside the road in windrows. The yarding crane is readily mobile, requiring only one to three guylines to be set before operation. Grapple or drop-line carriages may be used.

Grapple yarding may reduce yarding disturbance by: reducing the load size (only one log is yarded each time); reducing the clearance needed because the log does not hang from a choker; having narrower yarding road widths, that result in fewer logs passing over the third of the yarding road near the yarder; and directing the log around potential hang-up stumps by using the swing capability of the yarder (Sauder 1980). The dropline (choker) carriage will assemble turns of two or three (or more) logs per turn. The greater load size may produce more ground disturbance and the logs will hang lower because of the lengths of the chokers. Uphill or downhill yarding is possible with both variations.

The suspension of the butt rigging (chokers) using a block attached to the haulback on a highlead yarder converts the highlead system to a running skyline. There is improved control of the log in downhill yarding and improved lift on the front of logs in uphill yarding.

5.1.4 Long-line skyline systems

Long-line systems with multi-support cableways are used in Europe to log large areas of remote timber. The cableway, in effect, is a road. The Wyssen system has been used in British Columbia (Waelti 1976) to access timber where roads were not permitted (e.g., Greater Vancouver Watershed) or where road costs are too expensive for economical yarding (e.g., Vancouver Island and southern British Columbia coast). Although used to log some large old-growth stands in coastal areas of the province, daily production per yarder is low compared to conventional cable operations. Full suspension of logs requires the use of topographic features such as gullies, flood plains, or rising hillsides by placing tailholds in locations to maximize deflection. The yarder is relatively small compared to mobile tower yarders and pulls itself up the hillside. Logs can be moved long distances down the skyline by gravity, and thus road requirements are reduced.

The advantages notwithstanding, the long corridor needed for the cableway may itself cause problems. There have been at least four long-line yarders destroyed and wood burned because of fires that started at the landing and spread rapidly to the upper setting. In these cases, the cableway acted as a chimney and the fires spread too rapidly to be contained.

5.1.5 Balloon logging systems

Balloon logging has been shown to minimize yarding disturbance on long, steep, straight or slightly convex sideslopes (Dyrness 1972; Lysons 1974; Sauder 1976). Yarding distances up to 1500 m are possible (Conway 1976). Some yarding disturbance may occur before the logs are fully lifted and when they approach the landing, although loads are fully suspended for most of the yarding distance. Strong stumps are required to anchor the lines. Road access can be minimal compared to other cable systems.

Several problems with balloon yarding persist. A reliable, fast yarder with large line capacity and with sufficient strength to resist the constant upward pull of the balloon is not readily available. As well, there is the difficulty in spotting chokers precisely so they can be set quickly onto a turn; and the larger and longer lines required for the system require greater physical effort from the rigging crew than conventional systems. There are also problems associated with the balloon: a large clear area is required for bedding and tying down the balloon during storms, and for inspection and helium replacement; snow accumulation on the balloon needs to be cleared away; and the balloon is subject to low velocity winds during movement between the logging site and bedding ground (Lysons *et al.* 1966).

5.2 Aerial Yarding Systems

The helicopter logging system has the greatest potential to reduce mass wasting. Roads on steep slopes are not required, deflection is not important, tailhold anchors are not required, logs can be fully suspended, and cutting boundaries can be irregular. However, the system must be carefully evaluated when considered for steep terrain operation to ensure machine specifications for descent rate are not exceeded. Yarding distances within 1600 m are usually practical. As well, the system is susceptible to wind gusts, fog, and snow.

The S 64-F helicopter (9000 kg payload) requires up to 2000 L of fuel per operating hour; the S 61-L, payload capacity 4000 kg, requires 600 L per operating hour. Thus, a large consumption and expense for aviation fuel should be expected (Conway 1976). The helicopter can lift logs straight up, with little or no lateral yarding which reduces disturbance. However, the amount of debris remaining around the large central landing is greatest with the helicopter system because logs are brought to the landing with most of the limbs inplace and the helicopter landing handles considerably more timber than a conventional highlead landing. This concentrated volume of slash can present future problems for disposal and site regeneration. Greater volumes of residue remain over the setting after logging, which may enter streams and gullies. Small logs and broken pieces that accumulate in gullies are not removed because of the high cost of yarding (Guimier and Wellburn 1984). The extremely high cost of helicopter yarding excludes all but the most valuable stands in the Queen Charlotte Islands. The use of a helicopter to remove only the most valuable portion of the standing timber may result in the remaining timber always being uneconomic for logging.

5.3 Alternative Systems

When a skyline yarder is not available, two highlead towers can be used in tandem. The setup has been used successfully in British Columbia to operate a modified Tyler system (Studier and Binkley 1974; pers. comm. B. Vidal 1983). The Tyler system has the capability of reaching out to the side much like the North Bend system and can suspend logs provided there is adequate ground clearance.

Remote-controlled self-contained carriages can be mounted on a skyline to increase yarder versatility. These devices use radio controls to operate sensors on the carriage that set brakes and clamps or activate onboard drums. Some carriages have self-contained engines to power the tongline for choker inhaul and outhaul. The use of such complex carriages is worthwhile when there are not enough drums on an available yarder to operate a skyline system. However, the weight and bulk of remote-controlled carriages reduces the ground clearance available and decreases the deflection available for lifting loads.

6 CONCLUSIONS

The literature reveals that:

1. Mass wasting is a natural and common geomorphological process in steep slope regions worldwide and its occurrence and frequency are influenced by complex interactions among topographic, soil, climatic, and vegetative factors.
2. The principles, physical processes, and mechanics of mass wasting are well recognized.
3. In western North America, timber harvesting on steep slopes usually results in an increase in the frequency of mass wasting. The primary factors cited for these increases include road construction, logging disturbance, and deterioration of root strength following timber cutting and vegetation removal.
4. The role roads and root decay have in initiating mass wasting has received considerable research attention. However, references to the effects of yarding systems and yarding disturbance on mass wasting are infrequent, and evidence for such effects is indirect. No studies that specifically investigated the roles of different yarding systems and forms of yarding disturbance and the relationship of yarding disturbance to mass wasting were found.
5. Recommendations in the literature which favour one harvesting system over another are generally based on factors other than the operating characteristics of the yarding systems themselves. Cable-based rather than ground-based systems are promoted to reduce soil disturbance; and cable systems capable of yarding long distances are promoted to reduce the number of landslides by minimizing the amount of road on sensitive slopes.
6. Discussions of the role of harvest planning and layout typically concentrate on avoidance of sensitive sites. There has been no comprehensive study of the effectiveness of intensive logging planning as an approach to managing unstable slopes and minimizing landslides.

7 RECOMMENDATIONS

In addition to the literature review, FERIC interviewed operations personnel on the Queen Charlotte Islands. These people, employed by the forest companies, B.C. Ministry of Forests and Lands, and other agencies, are responsible for planning and directing logging.

During the discussions on how to improve logging and reduce its effect on mass wasting, the need for the following information was recommended:

1. Identify the specific road building or logging activities that have triggered mass wasting events. Determine whether alternative activities are available which may have eliminated or reduced the severity of the event. This recommendation resulted in the FERIC study, "A Forest Engineering Analysis of Landslides in Logged Areas on the Queen Charlotte Islands, B.C.", by Krag *et al.* (1986).
2. Determine how specific characteristics and operating techniques of different yarding machines and systems result in site disturbance which may lead to mass wasting. This information is needed to enable planners to predict the results from using alternative yarding methods. This recommendation resulted in the FERIC study, "Studies of Yarding Operations on Sensitive Terrain, Queen Charlotte Islands, B.C.", by Sauder *et al* (1987).
3. Determine the information required and available for adequate forest planning, road location, setting layout, and yarding system choice on steep sensitive sites. Review and test the planning procedures to determine if the information is available at the opportune time and if the referral and control procedures are conducive to planning for optimum results. This recommendation resulted in a third FERIC study, "Planning of Logging Operations on Sensitive Terrain, Queen Charlotte Islands, B.C.", by Sauder *et al.* (in prep).

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