Studies of Yarding Operations on Sensitive Terrain, Queen Charlotte Islands, B.C.

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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.

Studies of Yarding Operations on Sensitive Terrain, Queen Charlotte Islands, B.C.

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ABSTRACT

Fourteen yarding settings on eight different sites on the Queen Charlotte Islands were monitored to measure productivity and evaluate logging system effectiveness, to document yarding disturbance, and to determine how disturbance may contribute to landslide initiation. Twenty-three landslides occurred on or near the study areas, of which three occurred in adjacent control areas of no logging, and four occurred prior to yarding and were probably associated with discharge of road drainage. Of the sixteen failures that occurred within the yarded areas, fourteen had direct evidence of yarding disturbance in their initiation zones.

Nine of the failures (four road associated, three non-logging associated, and two yarding associated were over 200 m^2 in area). For the area of the study (1.065 km^2), and the time period (4 years since falling and 3.6 years since yarding), the frequency for logging failures (road and yarding) was 1.4 failures per km^2 per year, and for yarding failures was 0.5 failures per km^2.

The report describes various logging terms, yarding systems, and yarding disturbance forms. Production and yarding costs for highlead, mobile yarding crane (grapple and dropline carriage), and skyline yarding are presented. Operational factors that limit or promote particular system use on steep difficult terrain are documented.

The amount and causes of yarding disturbance are documented and related to the terrain yarding system requirements, yarding techniques, and operation. The importance of other factors (including falling of timber and vegetation removal) are also noted. The number, apparent causes, size, and time period of mass-wasting events are documented and related to the yarding system and setting.

The characteristics of sensitive sites on the areas studied are noted.

Finally, recommendations are made that can assist logging engineers and loggers in reducing yarding disturbance, increasing productivity, and reducing the potential for yarding-induced mass wasting.

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INTRODUCTION

This is the third 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 the results of 14 case studies and experiments on yarding in sensitive terrain.

In 1980, FERIC was asked by FFIP to determine if the use of skyline and helicopter-logging techniques on unstable slopes would reduce the frequency of landslides within clearcuts. The question inherently assumes that the yarding system, rather than how the system is applied, is more important in the logging of unstable slopes. In the past, many researchers have identified the truck road network as a source of landslides and have favoured skyline or helicopter yarding primarily because it reduces road lengths and secondly because it appears to reduce yarding disturbance (Dyrness 1967a, 1967b; Fredriksen 1970; Swanston 1970, 1971, 1976; Megahan 1972a; O'Loughlin 1972; Swanston and Dyrness 1973; Megahan *et al.* 1978; Schwab 1983). While the theoretical advantages of long-distance skyline yarders has been used to demonstrate a potential for less road, no one has established that they reduce overall site disturbance and mass wasting. The effects of root deterioration on slope stability has been researched and has been proposed to explain the tendency for increased landslide frequencies from 3-10 years following timber cutting (Bishop and Stevens 1964; Swanston 1969; Megahan *et al.* 1978; and Wilford and Schwab 1982).

The literature also suggests that yarding disturbance can contribute to landslide initiation by:

- redirecting and concentrating ground water to a central landing as occurs with downhill highlead yarding (Sidle 1980);
- allowing surface water to penetrate through to underlying consolidated material, accelerating the chemical weathering of bedrock after deep disturbance (Ballard and Willington 1975; Megahan 1972b);
- allowing logging debris to accumulate in deep V-notch gullies, creating dams that can break during peak flows and initiate debris torrents (Bishop and Stevens 1964; Swanson *et al.* 1976; Swanston 1976); and
- disturbing the upper soil layers where the extensive root networks (especially in the shallow soils of coastal B.C. and Alaska) provide a reinforcing membrane that hold the underlying soil in place (Sidle 1985).

Terrain specialists have also suggested there is potential to reduce landslides associated with yarding steep slopes by reducing disturbance (Bourgeois 1975[1]; Bourgeois and Townshend 1978[2]; Lewis 1979[3]; Townshend 1979[4]; Townshend 1981[5]). However, the linkages between accelerated mass wasting and yarding disturbance have not been clearly identified, nor have the various forms of yarding disturbance and their causes.

In this study we assumed:

- slope failures that occurred immediately after timber felling and prior to yarding were not yarding related;
- slope failures that occurred 3-4 years after felling and yarding were more associated with yarding than with root deterioration; and

[1] Bourgeois, W.W. 1975. Geotechnic inventory of a portion of Louise Island, Queen Charlotte Islands. Unpublished paper prepared by MacMillan Bloedel Ltd., Nanaimo, B.C.

[2] Bourgeois, W.W. and R.B. Townshend. 1978. Geotechnic inventory of a portion of Louise Island (Skedans Area); Addendum to 1975 report. Unpublished paper prepared by MacMillan Bloedel Ltd., Woodland Services Division, Nanaimo, B.C.

[3] Lewis, T. 1979. The ecosystems of Lyell Island, Queen Charlotte Islands, B.C. Unpublished paper prepared for Western Forest Products Ltd., Vancouver, B.C.

[4] Townshend, R.B. 1979. Geotechnic report - Rennell Sound, Queen Charlotte Islands. Unpublished paper prepared for CIPA Ind. Ltd., Vancouver, B.C.

[5] Townshend, R.B. 1981. Geotechnic report - Davidson, Cave and Haines Creeks, Queen Charlotte Islands. Unpublished paper prepared for CIPA Ind. Ltd., Vancouver, B.C.

- slope failures that occurred 4 or more years after felling and yarding were more associated with reductions in root strength than yarding.

To assess whether yarding systems are a direct cause of failures, the capabilities and limitations of the systems must be understood and the mechanisms initiating mass wasting must be clearly identified. The dragging of logs along the ground is the main direct physical link between the yarding process and the soil mantle. Therefore, ground disturbance is the key if yarding does contribute to failure initiation.

The objectives of this study were to:

- examine the operational performance and cost of yarding systems and techniques used on the Queen Charlotte Islands;
- determine whether perceived limitations of existing systems are related more to their application than to their physical capability (line and lift capacity);
- document and measure the various forms of yarding disturbance, describe how they occur in relation to yarding techniques and the yarding system, and determine how yarding disturbance can contribute to landslide initiation;
- observe changes in the number and frequency of landslides that occurred during the period of the study; and
- assess the potential for alternative yarding systems to reduce mass wasting within clearcuts.

2 STUDY METHOD

Between 1980 and 1984, 14 different settings were studied at eight different sites, and three different yarding systems were observed (Figure 1 and Table 1). All study sites had moderate to steep slopes where slope movements could occur, had portions of difficult yarding, and were typical of the more difficult sites that the Queen Charlotte Islands forest industry would be logging in the future.

Each setting was considered a separate case study. This allowed us to observe, separate, and compare yarding operations on a variety of potentially unstable terrain. The case-study approach acknowledged the complex interactions that exist between the ground, topography and terrain, the yarding process, environmental factors, climatic events, and subsequent slope failures. Detailed statistical comparisons between systems were not undertaken.

2.1 Study Procedure

Most study settings were walked before felling and all were walked before yarding. Gully systems on two study sites (Study Site Nos. 5 and 6) were mapped in detail before tree falling and logging (Figure 2a). The mapping noted areas of historic and active sidewall or channel failure, areas with and

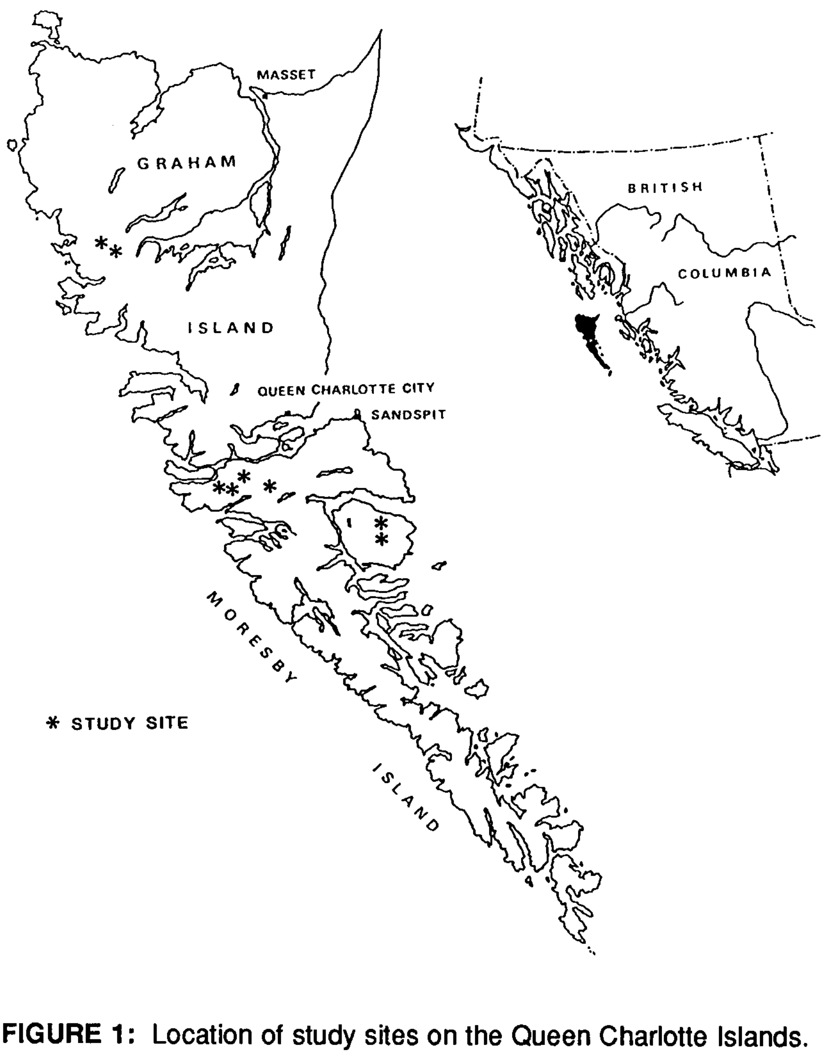


FIGURE 1: Location of study sites on the Queen Charlotte Islands.

TABLE 1. Summary of study sites

Study site	Year of study and logging	Study setting	Comments
1	1981	HL[a]-1 & SL[b]-1	Comparison of highlead to skyline - uphill yarding
2	1981	HL-2	Highlead (scabline) - uphill yarding
3	1981	YC[c]-1	Grapple yarding perpendicular and parallel to contours - uphill to downhill yarding
4	1982	YC-2	Grapple yarding moderate slope, full suspension over a creek - downhill yarding
5	1983 to 1984	YC-3, HL-5, HL-6	Grapple and highlead yarding a deeply gullied setting - uphill yarding
6	1983 to 1984	YC-4, HL-3, HL-4	Dropline and grapple yarding downhill, and highlead-uphill, a gullied setting
7	1983	SL-2	Gravity skyline - uphill yarding
8	1984	SL-3 & HL-7	Twin-tower skyline - downhill yarding, and highlead (scabline) -uphill yarding

[a] HL - highlead.

[b] SL - skyline.

[c] YC - yarding crane.

without vegetation, and detailed channel characteristics. Combining the detailed mapping with numerous photographs and a series of field reference points will allow for future monitoring of these gullies. In addition, unlogged adjacent gullies were mapped and used as controls.

The way in which logs were pulled into the landing during yarding operations, and the resulting yarding disturbance, were observed. Detailed time studies were carried out to determine operational characteristics and to provide basic production data.

Yarding roads were surveyed after yarding. Yarding disturbance greater than 1 m^2 in area and terrain features that occurred within 10 m of the cable path were noted on a "strip map" (Figure 2b). The yarding pattern was plotted and the size of the logged area determined. Yarding-road profiles and cable pathways were plotted for 6, 9, and 12% deflection.

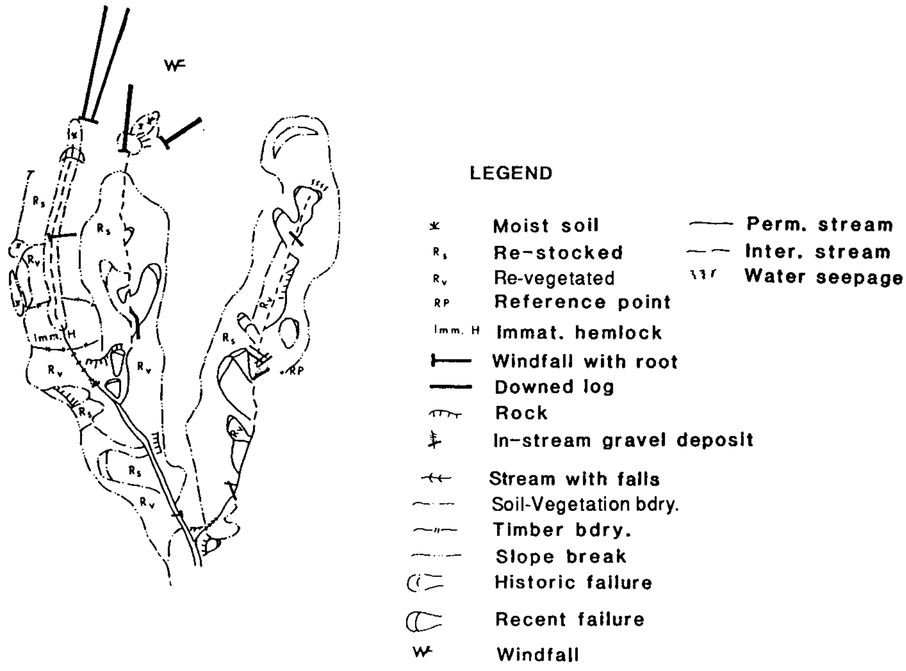


FIGURE 2a: Example of gully mapping.

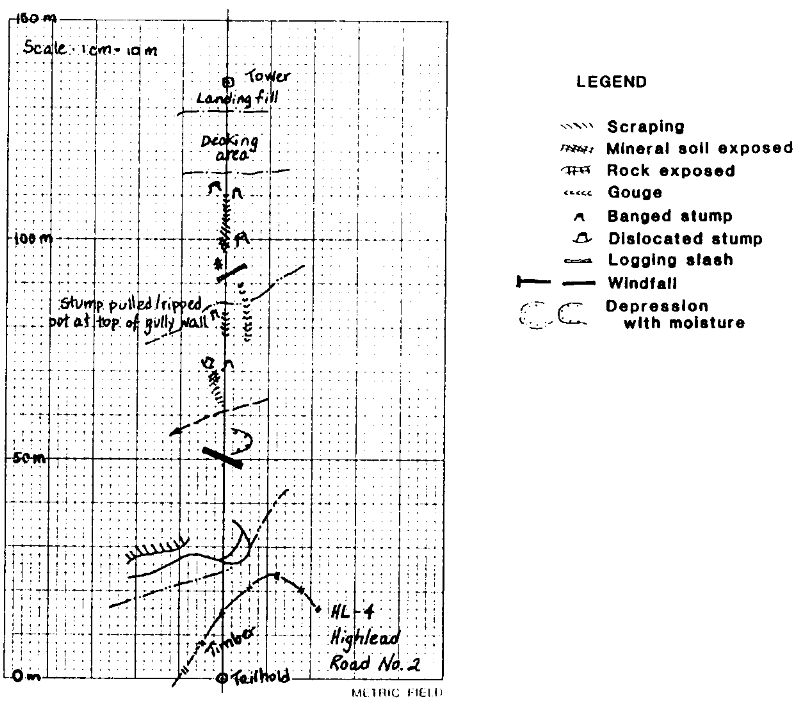


FIGURE 2b: Example of yarding road mapping.

FIGURE 2: Examples of field mapping.

All settings were re-examined at least twice after logging and the time period after logging varied from immediately to four years. Any slope movements that occurred between observations were noted. Gullies on Study Site Nos. 5 and 6 were also re-examined and the changes noted on the original gully maps.

Table 2 summarizes the number of yarding roads observed. The larger sample size for the yarding crane reflects the widespread usage of this system.

Detailed descriptions of each study site are available from FERIC.

TABLE 2. Number of yarding roads observed

	Number of yarding roads surveyed for:			
	Disturbance	%	Production	%
Highlead	24	30	29	20
Yarding Crane	31	38	84	59
Skyline	26	32	29	20
Total	81	100	142	99

3 LOGGING AND DISTURBANCE TERMS AND DEFINITIONS

This section defines the logging and disturbance terms used in this report. More detailed descriptions are found in Sauder *et al.* (1987).

3.1 Yarding Machines

The specifications of yarders observed during the study are given in Table 3. The most important factors to consider when matching a yarder a specific setting are tower height, line capacity, number of operating drums, and the line pull or power available to lift or pull logs.

TABLE 3. Yarder specifications

System	Yarder	Tower height (m)	No of guylines	Line capacity (m) for various diameters (mm)			Line pull (N) at mid drum		
				Mainline	Haulback	Skyline	Mainline	Haulback	Skyline
Highlead	Madill 009	27.1	6	32 mm — 430	22 mm — 1040		409 300	151 200	
	Skagit	30.5	6	35 mm — 380					
Running skyline	American 7280A	19.8	2	22 mm — 460	22 mm — 1220		311 800		
	Washington 118	16.4	2	22 mm — 490	22 mm — 1010		835 400	219 700	
Skyline	Madill 046	27.1	8	25 mm — 790	22 mm — 1620	22 mm — 700	489 300	222 400	987 300
	— studied	24.4		29 mm — 610	25 mm — 1220	35 mm — 380			
						38 mm — 490			

3.2 Highlead

Highlead is a simple yarding system (Figure 3a) which uses a mainline to pull the logs and a haulback to return the chokers. If no tension is applied to the haulback, the logs drag along the ground. If tension is applied, some lift is provided to the front of the logs (Figure 3b). Highlead can be used either uphill or downhill and works best on concave slopes (although it can also operate on convex slopes). Pull on anchor stumps is the least of all systems.

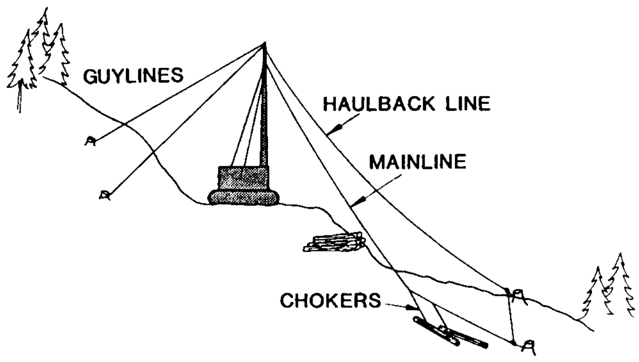
A highlead system can be converted to a simple running skyline (scabline) by using a rider block to support the load on the outgoing haulback (Figure 3c). This system provides lift to the front-end of inhauled logs (full suspension is possible in certain topography) and control during downhill yarding, but it requires stronger tailholds than conventional highlead and results in increased line wear.

Highlead spars require central landings and anchors for a least six guylines and are not mobile once set up.

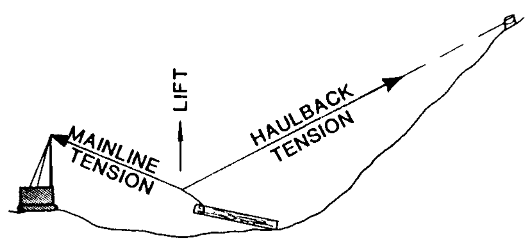
3.3 Skyline Systems

All skyline systems use a carriage that rides on a suspended cable, the skyline. Strong anchors are needed because of the extreme forces that can be exerted on the skyline tailhold and on the tower during yarding. This is particularly true where it is necessary to reduce the deflection to increase clearance. A variety of different skyline yarding systems are available, depending on the yarder capability, the ground shape, the direction of yarding, whether full or partial suspension is required, and the size of loads (Figure 4).

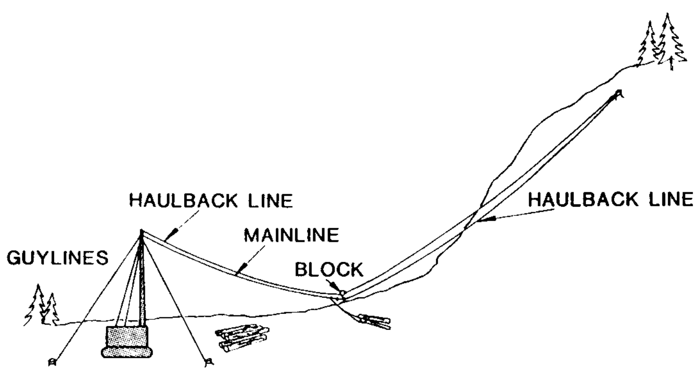
Riggers and machine operators must be skilled. The layout of the setting is critical to an efficient operation. Skylines will log uphill or downhill but cannot be used where the carriage would drag over the ground.



(a) Highlead yarding.



(b) Highlead 'lift'. Application of mainline and haulback tension creates 'lift' to the log.



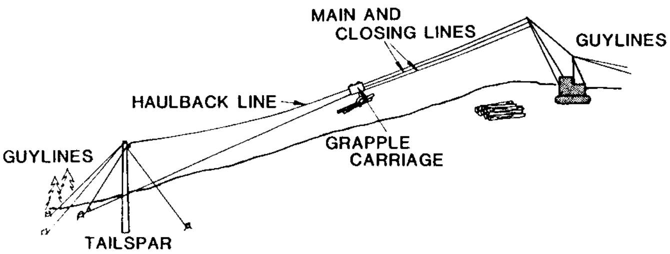
(c) Highlead simple running skyline (scabline).

FIGURE 3: Highlead yarding system and modifications. (Note: Not all guyline cables are indicated.)

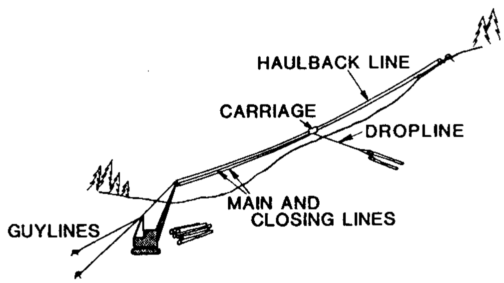
The skyline systems used in British Columbia until the 1960's often reached to 600 m. Occasionally, European systems have extended yarding to 800 m. Because of the concern over the inaccessibility of crews in case of accident, most yarding today is limited to distances of 400 m. Skyline systems can yard wide yarding-road widths that reduce the number of skyline changes.

3.3.1 Skyline tower-yarder

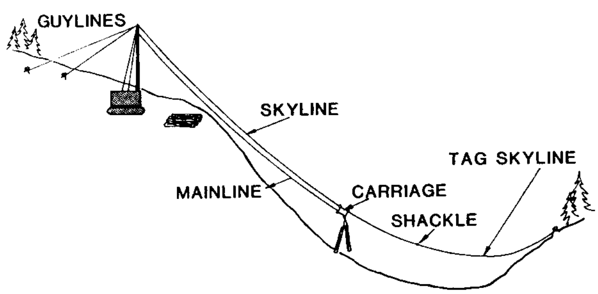
Skyline tower-yarders are portable tower yarders equipped with three or more yarding drums. They require a central landing, eight guyline stumps to support the tower, strong tailhold anchors to restrain the heavy pulls exerted by the winch, and more power or gearing than highlead machines to tighten the skyline and running lines. Logs can be fully or partially suspended depending on terrain configuration.



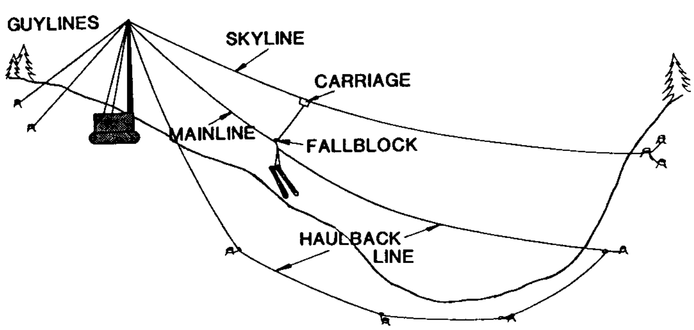
Running skyline with grapple.



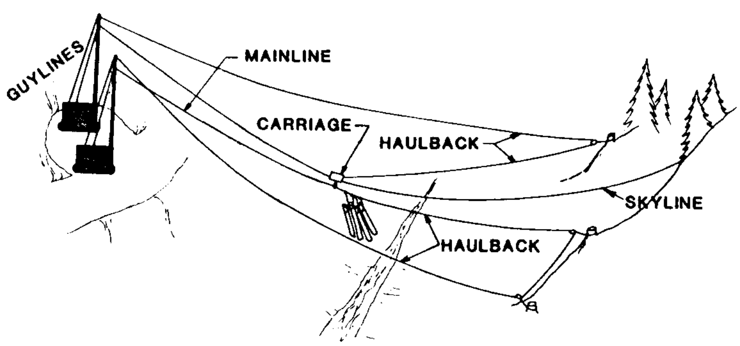
Running skyline with dropline.



Live (gravity) skyline.



North Bend.



Twin tower skyline.

FIGURE 4: Skyline yarding systems. (Note: Not all guyline cables are indicated.)

3.3.2 Yarding cranes

Mobile yarding cranes are self-propelled yarders that can swing their boom and require one to three guylines. They use a running skyline system (Figure 4), similar to a scabline, and a third line to operate a grapple or dropline carriage. Logs can be fully or partially suspended, depending on terrain configuration. Through the yarder's swing and mobility, logs can be windrowed beside the road or decked on the road, large central landings are not required, and the yarder can make use of the best available deflection. Yarder swing can also be used to redirect logs around difficult yarding or sensitive terrain.

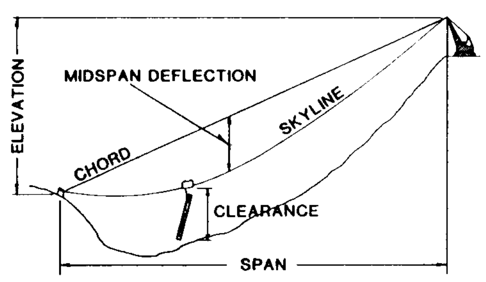
3.4 Deflection and Clearance

Deflection is a measurement of the sag in a cable. It is the vertical distance between the chord (an imaginary line between the head spar and the tailhold) and the skyline (Figure 5). Deflection is expressed as a percentage of the horizontal span and is measured at midspan. Deflection is controlled by the horizontal and vertical distance between the yarder and the tailhold, the shape of the terrain, the strength and weight of the lines, the weight of the lifted logs, and the power of the yarder. Most skyline operators assume that minimum skyline midspan deflection is between 5 and 8%. Deflection is also used colloquially to describe the yarding chance. Good deflection implies good yarding with no hangups, whereas poor deflection implies difficult yarding and poor production.

The amount of clearance depends upon ground profile and deflection. An efficient cable system should drag logs so the front of logs do not hit stumps or dig into the ground. This can be achieved if the front of the logs are raised above stump height during inhaul.

3.5 Yarding Distances

The definition of external yarding distance varies but generally denotes the distance from the landing to the yarding boundary. For example, in the planning of setting layouts on maps, it refers to the horizontal distance from the landing to the cutting boundary. However, in the designing of individual yarding roads it refers to the slope distance measured from the top of the tower to the yarding boundary. In this report it refers to the maximum horizontal yarding distance logs were yarded for the road under discussion. The chord distance refers to the slope distance from the tower to the tailhold and may be longer, the same, or shorter than the external yarding distance.



$$\text{Midspan deflection (\%)} = \frac{\text{deflection distance at midspan}}{\text{span distance}} \times 100$$

FIGURE 5: Skyline terms.

3.6 Logging Chance

Logging chance is defined as the opportunity for the yarder to operate with satisfactory production using the system's capabilities for payload, yarding distance, and yarding road spacing. Operating factors, such as deflection, lift, and landing location, contribute to the logging chance. Logging chance is expressed as good, fair, or poor.

3.7 Mass Wasting Forms

The terms landslide, slope movement, failure, and slope failure are collectively used in this report to describe the forms of mass wasting associated with the rapid downslope movement of soil and debris. Geologic and climatic conditions combine to create naturally unstable conditions and to initiate landslides during major storm events throughout mountain regions. Road construction and logging accelerate natural landslide frequency levels (Fredriksen 1970; Swanston and Dyrness 1973; Swanson and Dyrness 1975; Schwab 1983).

The three kinds of slope movements associated with timber harvesting on the Queen Charlotte Islands (Varnes 1978; Wilford and Schwab 1982) are:

1. debris slides - shallow, rapid, downslope movements of unsaturated surficial material and organic debris.
2. debris flows - shallow, rapid, downslope movement of saturated soil and organic debris, usually confined to a depressional channel.
3. debris torrents - the rapid movement of saturated debris down steep V-notch gullies.

3.8 Yarding Disturbance Terms

In this report, yarding disturbance is defined as any yarding or operational event, other than truck roads and landings, that could conceivably lead to displacement of soil or changes in soil structure, and so contribute to landslide initiation.

Yarding disturbance was divided into two categories: shallow and deep. Shallow disturbance (scraping) was not expected to lead to mass wasting unless it occurred over an area large enough to alter ground water flows. Shallow disturbance was restricted to disturbance of the litter layer and was generally less than 5 cm deep. Deeper disturbance may lead to mass wasting because it provides an opportunity for water to enter deeper layers of the soil. The following were classified as deep soil disturbance:

- mineral soil exposure, where the mineral soil was exposed, allowing direct water penetration;
- rock exposure, where the thin layer of organic material over-lying the rock was scraped away. The rock was exposed to the increased effects of weathering;
- gouging, where a compacted base was formed into a ditch that could accumulate and redirect water to adjacent areas;
- disturbance to infilled depressions or historical slope movements (e.g., an old slide) which disrupted natural drainage patterns; and
- stump dislocation which could reduce root strength and allow water to enter deeper soil layers by way of the root channels.

4 STUDY RESULTS

4.1 Production and Costs

The machine duty cycles on each study setting were timed and recorded to provide data for production and yarding costs. Production was calculated by multiplying the number of pieces logged by an average log size of 1.8 m^3 for all settings. While this reduces the accuracy of results for an individual setting, it increases the comparability of results between systems and settings. The 8-hour shift piece counts included actual delays and yarding road changes. Move time from one setting to the next was not included because production was not monitored over complete settings and a pro-rated move time could not be determined. The production costs were obtained by multiplying the hourly cost for the yarder used (Table 4) by the shift length (8 hours) and dividing by the production per shift. Operating and machine ownership charges were included but interest on the money invested, supervision, and administrative costs were excluded.

A summary of characteristics measured from yarding-road profiles and the yarding chance is presented in Table 5. Differences in external yarding distances between Table 5 and the succeeding production summaries are attributed to differences in yarding-road lengths during data collection. Not all surveyed roads were timed in detail, nor were all detail - timed yarding roads surveyed. On roads that were not surveyed, the external yarding distance was estimated.

4.1.1 Highlead

Table 6 shows the setting characteristics, productivity, and costs for the highlead studies. Performance was dependent on the setting characteristics and yarding distance. When the slope was concave (HL-2), logs were yarded with little difficulty. As highlead was the only system that could yard the settings where deflection was minimal (HL-3 and HL-5), it was relegated to difficult settings where no other cable system could perform satisfactorily and costs and productivity were adversely affected.

Highlead was also used to log long corners (HL-1) where there was little lift for over half of the yarding road. This reduced productivity and increased costs.

In our studies we observed that highlead yarding:

- required a central landing, which resulted in concentrated disturbance around the landing;
- required a full-time log loader on steep sideslopes;
- could yard further over convex terrain than the mobile yarding crane because of its greater tower height and because the rigging can be dragged on the ground;
- caused logs to move downhill as they were yarded parallel to the contours of a steep slope;
- could partially support logs when a rider block was attached to join the haulback and butt rigging (scabline), and when there was sufficient deflection;
- required a five-to six-man crew;
- took 3-4 hours to set up when the guyline anchor stumps had been pre-selected and notched; and.
- allowed good production between 250 and 340 m. Beyond 340 m, productivity dropped off quickly.

4.1.2 Yarding crane

Yarding crane performance was evaluated in operation with either a grapple or a dropline carriage and chokers (Table 7). Although deflection is important to the operation of the yarding crane, local areas of poor yarding can be improved by moving the yarder and yarding from a different angle.

TABLE 4. Summary of operating and ownership costs

	Highlead	Skyline			Yarding Crane			
	Madill 009 Highlead	Madill 009 Shotgun	Madill 009 Twin Tower	Madill 046 Slackline	Washington 118 Yarding Crane Grapple	Washington 118 Yarding Crane Dropline	American 7280A Yarding Crane Grapple	American 7280A Yarding Crane Dropline
OWNERSHIP COSTS – INPUT								
Purchase price ($)	$470 000	$483 105	$912 710	$637 613	$780 000	$780 000	$850 000	$850 000
Salvage value (s)	$30 000	$30 000	$75 000	$50 000	$156 000	$156 000	$170 000	$170 000
Expected life (yr)	13	13	13	13	9	9	9	9
Expected life (h)	16 380	15 600	15 600	13 000	11 700	11 700	11 700	11 700
Usage per year (h)	1 260	1 200	1 200	1 000	1 300	1 300	1 300	1 300
Interest rate (Int.) (%)	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Insurance rate (Ins.) (%)	1..5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
OWNERSHIP COSTS – RESULTS								
Average investment (AVI) = (P+S)/2	$250 000	$256 553	$493 855	$343 807	$468 000	$468 000	$510 000	$510 000
Loss in resale value = (P-S)/h	$26.86	$29.05	$53.70	$45.20	$53.33	$53.33	$58.12	$58.12
Interest = (Int. x AVI)/(h/yr)	$24.80	$26.72	$51.44	$42.98	$45.00	$45.00	$49.04	$49.04
Insurance = (Ins. x AVI)/(h/yr)	$2.98	$3.21	$6.17	$5.16	$5.40	$5.40	$5.88	$5.88
OPERATING AND REPAIR COSTS – RESULTS								
Line costs ($/h)	$29.00	$31.54	$30.10	$44.36	$45.52	$59.62	$41.71	$54.24
Rigging costs ($/h)	$6.35	$5.83	$3.67	$4.40	$7.50	$8.65	$7.50	$8.65
Fire suppression costs ($/h)	$1.19	$1.10	$1.25	1.38	$1.02	$1.02	$1.02	$1.02
Hourly fuel cost ($/h)	$16.20	$13.50	$31.50	$13.50	$11.25	$11.25	$18.00	$18.00
Lube and oil cost ($/h)	$1.62	$1.35	$3.15	$1.35	$1.13	$1.13	$2.03	$1.80
Repair and maintenance cost ($/h)	$27.78	$29.17	$36.67	$40.00	$65.38	$53.85	$69.23	$57.69
Labour cost ($/h)[a]	$101.01	$103.66	$146.01	$122.24	$64.89	$84.65	$85.31	$103.69
TOTAL OPERATING AND REPAIR COST ($/h)	$183.15	$186.15	$252.35	$227.23	$196.69	$220.17	$224.80	$245.09
TOTAL COSTS –RESULTS								
Loss in resale value ($/h)	$26.86	$29.05	$53.70	$45.20	$53.33	$53.33	$58.12	$58.12
Insurance ($/h)	$2.98	$3.21	$6.17	$5.16	$5.40	$5.40	$5.88	$5.88
Operating and repair costs ($/h)	$183.15	$186.15	$252.35	$227.23	$196.69	$220.17	$224.80	$245.09
TOTAL MACHINE COST (excluding interest) ($/h)	$212.99	$218.40	$312.22	$277.59	$255.42	$278.90	$288.8	$309.09
Interest cost ($/h)	$24.80	$26.72	$51.44	$42.98	$45.00	$45.00	$49.04	$49.04
TOTAL MACHINE COST (including interest) ($/h)	$237.79	$245.13	$363.67	$320.56	$300.42	$323.90	$337.84	$358.13
INCREASED COST WITH ALTERNATIVE CREW	$18.37	$18.58	$18.58					

[a] Basic crew consists of the yarder operator, landingman, and a hooktender.
A rigging slinger was required for highlead, dropline, and skyline yarding.
One chokerman, and often two (alternative crew), were used for highlead, shotgun, and twin tower yarding.
Two chokermen were used with the Madill 046 yarder.
One hooker and rigger was used to rig backspars with the American 7280A yarding crane.

TABLE 5. Summary of yarding-road characteristics and yarding chance (from yarding-road profiles)

System	Study site	Horizontal span (m) (from landing) Min.	Horizontal span (m) (from landing) Max.	Chord slope (%)[a] (from landing) From	Chord slope (%)[a] (from landing) To	Chord distance (m) (from landing) Min.	Chord distance (m) (from landing) Max.	External yarding distance (m) (from landing) Min.	External yarding distance (m) (from landing) Max	Lift deflection available (%) at midspan Min.	Lift deflection available (%) at midspan Max.	Weighted average deflection at (%) Front	Weighted average deflection at (%) Mid.	Weighted average deflection at (%) Back	No. of roads	Yarding chance
Highlead	HL-1		374		-28		392		392		5	8	5	1	1	poor
	HL-2	225	286	-38	-41	241	307	190	286	11	15	16	13	14	5	good
	HL-3	328	355	-56	-63	383	406	371	383	4	6	5	5	5	3	poor
	HL-4	140	271	-34	-40	149	290	149	263	4	7	8	5	7	4	poor
	HL-5	177	328	-34	-62	208	368	181	368	3	19	5	8	8	6	poor
	HL-6	301	355	-45	-50	330	398	313	398	5	12	8	10	5	4	poor
	HL-7		290		-7		291		291		14	12	14	9	1	fair
Yarding Crane	YC-1	67	157	-37	+30	70	159	70	159	5	21	15	11	8	5	good—poor
	YC-2	166	210	+28	+30	173	219	173	219	5	10	9	8	4	5	good
	YC-2a		263		+6		264		264		6	13	6	5	1	fair—good
	YC-3	119	324	-10	-43	120	341	120	344	5	16	12	9	10	13	good
	YC-4	258	357	+44	+57	289	396	285	390	7	13	10	10	8	7	fair
Skyline	SL-1		398		-19		405		418		6	7	6	7	1	good
	SL-2	237	371	-41	-68	269	434	231	373	6	14	10	9	8	23	fair
	SL-3	431	462	+22	+23	442	474	391	403	10	12	14	11	7	2	fair

[a] Chord slope is positive for downhill and negative for uphill yarding.

TABLE 6. Highlead yarding detailed timing results

Study site	No. of hours observed	Total no. of turns	Total no. of logs	Avg no. logs/turn	Maximum yarding distance[a] (m)	Deflection		Road changes		Production/8-hour shift[b]				
						Mid	Back	No.	Avg time (min)	Turns	Logs	Volume (m^3) @ 1.8 m^3 per log	Machine cost per hour[c] ($)	Cost ($/m^3$)
HL-1	19.9	136	264	1.9	350-390	poor	poor	3	33	55	106	191	278[d]	11.64
HL-2	28.8	276	633	2.3	180-290	good	good	4	21	77	176	317	222[e]	5.61
HL-3	13.0	73	197	2.7	330-380	poor	poor/ fair	3	46	45	121	218	222	8.14
HL-5	22.9	156	360	2.3	130-370	fair/ poor	fair/ poor	6	32	54	126	226	222	7.85
HL-6	25.4	192	243	1.3	310-400	poor/ fair	poor	5	24	60	77	138	222	12.89
HL-7	17.9	130	264	2.0	170-330	good	fair	5	36	58	118	212	222	8.36

[a] Range of maximum yarding distances where detailed timing studies were carried out (distances from tower).
[b] Includes road changes and excludes yarder set-up.
[c] Excludes interest costs.
[d] Setting yarded with Madill 046 slackline yarder.
[e] Madill 009 highlead yarder with 1.5 chokermen per shift. ($212.99 + 0.5 x $18.37 = $222.18)

TABLE 7. Mobile yarding crane detailed timing results

Study site	No. of hours observed	Total no. of turns	Total no. of logs	Avg no. logs/turn	Maximum yarding distance[a] (m)	Deflection: Mid	Deflection: Back	Road changes: No.	Road changes: Avg time (min)	Production/8-hour shift[b]: Turns	Production/8-hour shift[b]: Logs	Production/8-hour shift[b]: Volume (m^3) @ 1.8 m^3 per log	Machine cost per hour[c] ($)	Cost ($/m^3$)
Combined grapple and dropline														
YC-1	21.1	413	465	1.1	70-160	good/ fair	good/ fair	4	12	157	176	317	255[d,e]	6.43
YC-2	86.5	1639	2001	1.2	60-310	good/ fair	good	31	22	152	185	333	258[d,e]	6.20[a]
YC-2a	23.4	389	455	1.2	230-290	fair/ good	fair/ good	5	38	133	156	280	255[d,e]	7.29
YC-3	98.2	991	1521	1.5	75-350	good/ fair	fair/ good	24	32	81	124	223	266[d,e]	9.54
YC-4	73.8	362	743	2.1	75-400	fair	fair/ good	10	61	39	81	145	306[d,e]	16.89
Grapple only														
YC-1	21.1	413	465	1.1	70-160	good/ fair	good/ fair	4	12	157	176	317	255[e]	6.43
YC-2	75.4	1534	1698	1.1	0-310	good/ fair	good/ fair	28	21	163	180	324	255[e]	6.29
YC-2a	23.4	389	455	1.2	230-290	fair/ good	fair/ good	5	38	133	156	280	255[e]	7.29
YC-3	53.5	735	782	1.1	125-325	good/ fair	fair/ good	18	25	110	117	210	255[e]	9.69
YC-4	12.7	59	70	1.2	300-400	fair	fair/ good	3	98	37	44	79	289[f]	29.13
Dropline only														
YC-2	11.0	105	303	2.9	140-190	fair	fair/ poor	3	33	76	220	397	279[e]	5.63
YC-3	44.7	256	739	2.9	75-350	fair	fair/ good	6	52	46	132	238	279[e]	9.38
YC-4	61.1	303	673	2.2	75-300	fair/ good	good/ fair	7	46	40	88	159	309[f]	15.59

[a] Range of maximum yarding distances where detailed timing studies were carried out (distance from landing).

[b] Includes road changes and excludes yarder set-up.

[c] Excludes interest costs.

[d] Weighted average (hours grapple ydg. x hourly cost + hours dropline ydg. x hourly cost)/total hours.

[e] Washington 118 yarder, including only one hooker during grapple yarding and a rigging slinger when dropline yarding.

[f] American 7280A yarder, including a backspar rigger for grapple and dropline yarding.

The best grapple production occurred on concave settings with good visibility for the operator. For example, the production on YC-1 varied from high production (470 m^3 per shift) at the lower concave slope (good deflection) to poor production (180 m^3 per shift) along the upper slope (poor deflection). Full suspension to protect a stream at the front of a setting (YC-2a) and gully walls on a setting (YC-3) resulted in reduced grapple production. Grapple production on YC-4 was very poor because the operator was learning to operate the yarder, and he frequently tangled the lines. This study is included because it shows the increased costs that occur when performance is not satisfactory.

A dropline carriage was used on YC-2 to log small logs and on YC-3 to increase log production. The grapple normally yards one log at a time, whereas the dropline can yard two or more logs (especially when logs are small) and maximize payloads. As the yarding distance increases, the increased turn size offsets the time required to set the chokers and the cost of the extra crew required.

We observed that the mobile yarding crane:

- did not require a central landing and was able to windrow logs along truck roads;
- did not require a dedicated log loader;
- minimized the concentration of yarded logs over any given yarding road;
- directed the front-ends of logs along a path immediately below the running lines regardless of slope direction;
- aligned itself to achieve maximum deflection and the most advantageous gully crossing;
- fully or partially supported logs where ground clearance and deflection were adequate;
- required sufficient clearance to ensure the carriage and grapple did not catch on stumps or drag along the ground;
- worked efficiently with a three-man crew when grapple yarding, and a four-man crew when dropline yarding;
- was fast to set up (1-2 hours) and take down (less than 1/2 hour); and
- achieved yarding distances up to 360 m but distances beyond 275-300 m usually required a backspar. The majority of yarding distances were between 150 and 250 m.

4.1.3 Tower skylines

FERIC studied three different types of skyline systems: SL-1 used the North Bend system, SL-2 used the gravity (shotgun) system,and SL-3 used two highlead towers working together.

Skyline yarders can have higher towers (up to 9 m more), have greater line capacity, and have more line pull than highlead tower yarders or yarding cranes. The particular Madill 046 we studied had a short tower (24.4 m) as a result of a previous accident.

Skylines are used to provide lift and increase yarding distance. Skyline systems (except shotgun) can avoid dragging logs over sensitive sites because yarding roads are spaced wider apart than those required for highlead or yarding-crane logging, and because they can fully suspend logs when the yarding-road profile permits.

Table 8 summarizes the production and estimated costs of the systems. Production on SL-2 suffered because of delays when the skyline broke. For SL-3 the company did not have a specialized skyline tower. They attempted to provide full suspension by using two highlead towers, one for the skyline and one for the main and haulback lines. The system was slow and expensive and was stopped when two guylines broke and the skyline tower tipped over.

TABLE 8. Skyline yarding detailed yarding results

Study site	No.of hours observed	Total no. of turns	Total no. of logs	Avg no. logs/turn	Maximum yarding distance[a] (m)	Deflection		Road changes		Production/8-hour shift[b]				
						Mid	Back	No.	Avg time (min)	Turns	Logs	Volume (m^3) @ 1.8 m^3 per log	Machine cost per hour[c] ($)	Cost ($/$m^3$)
SL-1	18.7	95	263	2.8	325-420	fair/ good	good/ fair	1 H.B. 1 Sky & H.B.	27 124	41	113	203	268[d]	10.59
SL-2	148.9	937	2055	2.2	225-375	fair/ good	fair/ good	24	18	50	110	199	228[e]	9.18
SL-3	6.8	25	42	1.7	390-400	good/ fair	fair	1 H.B.	29	29	49	89	322[f]	28.96

[a] Range of maximum external yarding distances where detailed timing studies were carried out.
[b] Includes road changes and excludes yarder set-up.
[c] Excludes interest costs.
[d] Madill 046 Slackline yarder with 1.5 chokermen per shift.
[e] Madill 009 Shotgun yarder with 1.5 chokermen per shift.
[f] Madill 009 twin towers with 1.5 chokermen per shift.

In our studies we observed that skyline yarding:

- required a central landing located to maximize deflection;
- required a dedicated log loader when working on steep slopes;
- could fully suspend logs provided there was sufficient deflection and ground clearance;
- could partially support heavy turns to allow the front ends of yarded logs to clear stumps during uphill yarding;
- used its greater line capacity to yard long corners and to reach beyond the setting boundaries to increase deflection;
- used its tower height to provide increased deflection in the front part of settings and increased lift when used for high lead yarding;
- required a five -to six-man crew, two of whom were highly skilled;
- took at least 4-6 hours to set up when the guyline stumps and the skyline anchor stumps had been pre-selected and prepared; and
- showed the best yarding productivity between 250 and 350 m, but was still productive at 400 m. All yarding roads were longer than 200 m.

4.2 Yarding Road Densities

The amount of yarding road required to log a setting is related to the distance between yarding roads, the logging system, the yarding distance, and the terrain. Yarding crane and skyline logging required 30 and 50 percent less yarding roads per logged hectare, respectively, compared to highlead (Table 9).

The poor deflection and the strongly convex terrain contributed to the high yarding road density on HL-3. These factors restricted the width of yarding roads (especially at the back of the setting) to less than two choker widths (8-10 m). The low road density on YC-4 reflected the use of a dropline

TABLE 9. Yarding road density

Study	Area logged (ha)	No. of yarding roads	Yarding roads per ha logged
HL-1	1.09	5	4.59
HL-2	1.56	8	5.13
HL-3	0.39	5	12.82
HL-4	2.21	11	4.98
HL-5	1.56	8	5.13
HL-6	2.02	9	4.46
HL-7	1.30	5	3.85
Total highlead	10.13	51	5.03
YC-1	2.94	12	4.08
YC-2	6.23	34	5.46
YC-3	5.72	23	4.02
YC-4	6.50	10	1.54
Total yarding crane	21.39	79	3.69
SL-1	1.54	2	1.30
SL-2	6.96	25	3.59
SL-3	3.32	2	0.60
Total skyline	11.82	29	2.45

carriage and chokers, rather than a grapple that was used for most of the other yarding-crane settings. Yarding-crane logging resulted in wider and more rectangular-shaped yarding roads compared to the radial pattern of stationary towers. Dropline yarding roads were wider than those grapple yarded because there was a longer distance available to reach-out to hook-up logs. All yarding-crane roads were stump or backspar rigged and this probably resulted in the maximum distance between roads and the minimum number of road changes.

The skyline-yarding road densities were related to the particular skyline system used. The gravity system (SL-2) had the greatest skyline road density because the distance between roads at the back of the setting was usually less than 10-12 m or two choker lengths. The road density was greatly reduced when using a skyline system that had the capability to pull the chokers out to the side (SL-1 and SL-3).

4.3 Yarding Disturbance

Table 10 shows the logging chance, yarding disturbance for individually examined yarding roads, and the adjusted yarding disturbance per hectare of logged area on the settings studied. As expected, yarding disturbance on individual roads was most severe on settings with the poorest chance. Disturbance on these yarding roads would not have improved if a different cable system was used. In fact, highlead was the only system which would work on the areas with no deflection. These settings would have to be completely re-engineered to determine whether a different haul road network and alternative landing locations would have improved the yarding chance.

The least total and deep disturbance on individual yarding roads examined occurred on the areas logged with the yarding crane. The greatest total disturbance to individual yarding roads occurred on areas logged using a skyline system. The greatest deep disturbance results per road examined were adjusted to reflect the density of yarding road required to log a hectare of area (Table 9), the yarding crane had the least disturbance, and highlead had the greatest. This need to adjust for the yarding road density resulted in some settings that had high lengths of disturbance on individual roads having less disturbance on a setting - wide bases (e.g. YC-2, HL-6, and SL-3) and vice versa (YC-1 and SL-2).

The greatest length of disturbance on individually examined yarding roads occurred on HL-1 when large logs were yarded uphill over a convex slope. Settings HL-5 and HL-6 also lacked lift but the logs were smaller. Setting HL-5 was difficult because of a steep convex slope break which directed the logs into the same track and concentrated disturbance. Setting HL-2 had good deflection, but also wet, fine - textured soils that were easily disturbed.

The disturbance on individual examined yarding roads on SL-3 was caused by log ends sweeping off a gully edge before being fully suspended, and contacting the ground on landing. Part of this setting had soft wet organic soils that were easily disturbed.

The least disturbance on individually examined yarding roads was on YC-1 (primarily the lower portion), which had the shortest yarding distance. Setting YC-3 was yarded with special care to avoid disturbing a gully. Some gouging occurred when logs were yarded up a moist convex slope in front of the landing.

4.4 Factors Contributing to Yarding Performance and Yarding Disturbance

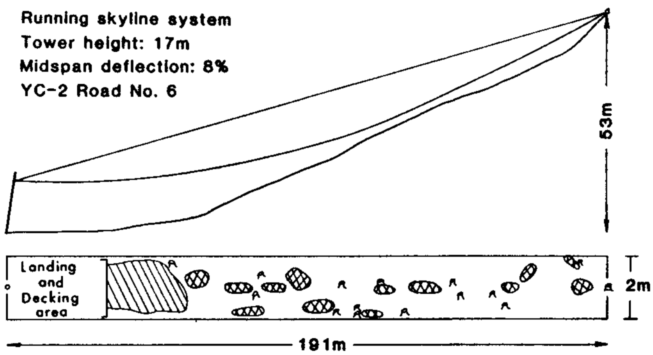
4.4.1 Natural ground features and yarding chance

Yarding chance was associated with yarding performance. Locating downhill yarding landings well away from the hillside (as in YC-2) improved the yarding chance (Figure 6a). The remaining good settings (SL-1, HL-2, and YC-3) were uphill yarded and their performance was improved because the tailhold locations were on a rising hillside across a gully or stream (Figure 6b-d). Study YC-1(Figure 7) was a typical setting where yarding chance progressed from good to poor as the yarding roads changed from straight uphill over a concave slope (good), to yarding across the sidehill (straight to convex slope), and finally to yarding downhill over a generally convex slope (poor).

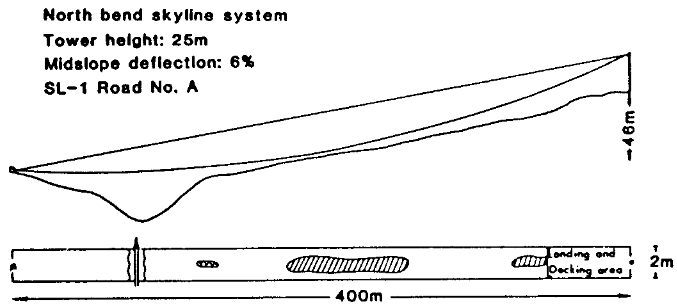
TABLE 10. Summary of yarding disturbance

Study site	Study setting	Yarding chance	Accumulated and average horizontal yarded span (m)	Lengths of disturbance (m): Shallow	Deep					Total distur— bance	Adjusted length of disturbance on yarding roads per logged area(m/ha)		
				Scraping	Mineral soil exposed	Rock exposed	Gouging	Disturbance within depression	Total deep		Shallow	Deep	Total
	Highlead												
1	HL-1	poor	374		154		36		190	190	0	872	872
	Avg[a]		374		154		36		190				
2	HL-2	good	1020		124	3	108		235	235	0	241	241
	Avg		204		25	<1	22		47	47			
6	HL-3	poor	981	138	62		212	14	288	426	590	1231	1821
	Avg		327	46	21		71	5	96	142			
6	HL-4	poor	728	76	16		54		70	14	95	87	182
	Avg		182	19	4		13		18	37			
5	HL-5	poor	1499	189	228	6	161	30	425	614	162	363	525
	Avg		250	31	38	<1	27	5	71	102			
5	HL-6	poor	1247	167	215	39	187	34	475	642	186	529	715
	Avg		312	42	54	10	47	8	119	161			
8	HL-7	fair	290	9	64		25		89	98	35	342	377
	Avg		290	9	64		25		89	98			
	Total		6139	579	863	48	783	78	1772	2351	121	372	493
	Avg		256	23	36	2	33	3	74	97			
	Yarding Crane												
3	YC-1	good-poor	454	39	30		39		69	108	32	56	88
	Avg		91	8	6		8		14	22			
4	YC-2	good	1176	145	78		76		154	299	132	140	272
	Avg		196	24	13		13		26	50			
5	YC-3	good	2895	151	137	28	176	53	394	545	47	122	169
	Avg		223	12	11	2	13	4	30	42			
6	YC-4	fair	2126	115	128	38	52	14	232	347	25	51	76
	Avg		304	17	18	5	7	2	33	50			
	Total		6651	450	373	66	343	67	849	1299	54	101	155
	Avg		215	15	12	2	11	2	27	42			
	Skyline												
1	SL-1	good	398	74						74	96	0	96
	Avg		398	74						74			
7	SL-2	fair	6016	1215	726	232	404		1362	2577	190	213	403
	Avg		262	53	31	10	18		59	112			
8	SL-3	fair	780	47	165	16	69		250	297	14	75	89
	Avg		390	24	83	8	34		125	149			
	Total		7194	1336	891	248	473		1612	2948	126	152	278
	Avg		277	51	34	10	18		62	113			

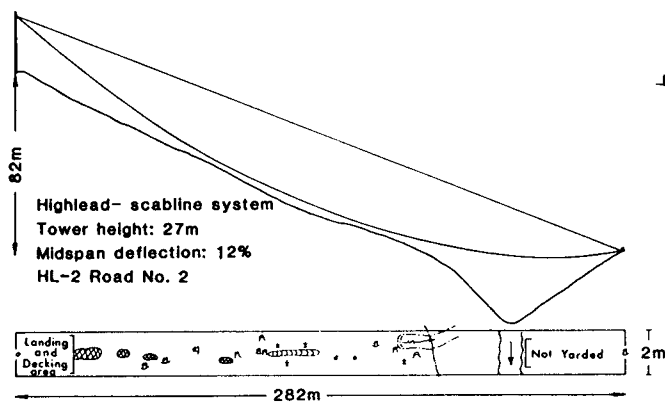
[a] Average yarding disturbance per road.



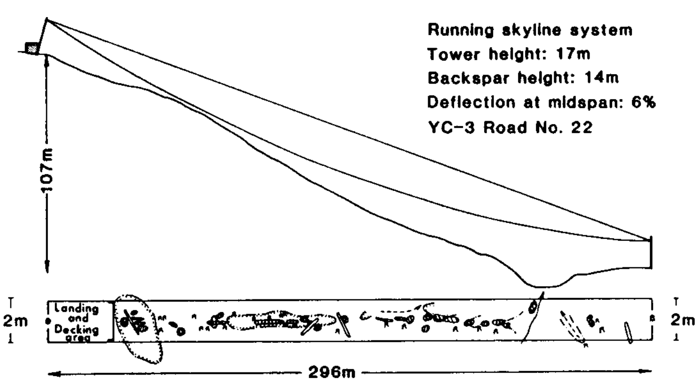
(a) Landing location away from hillside contributes to deflection.



(b) Tailhold location across stream contributes to deflection.

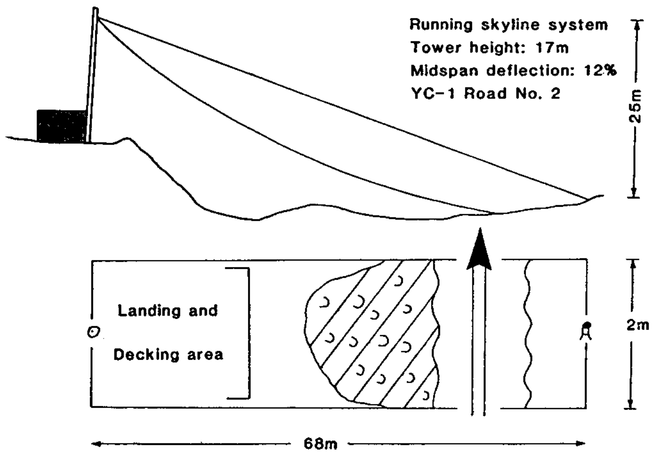


(c) Tailhold on rising hillside contributes to deflection.

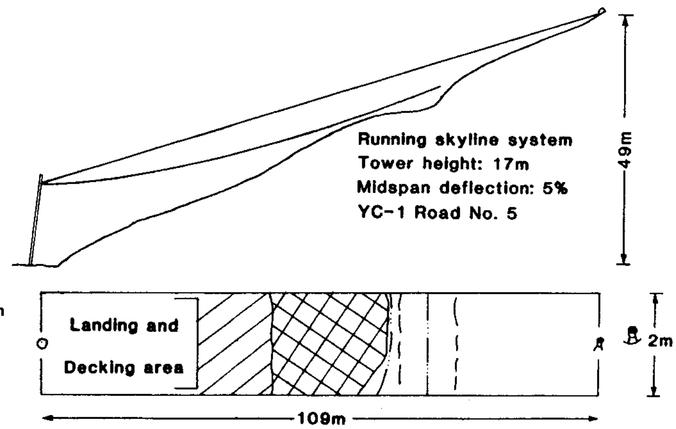


(d) Tailhold on gully edge and tower at roadside edge contributes to deflection.

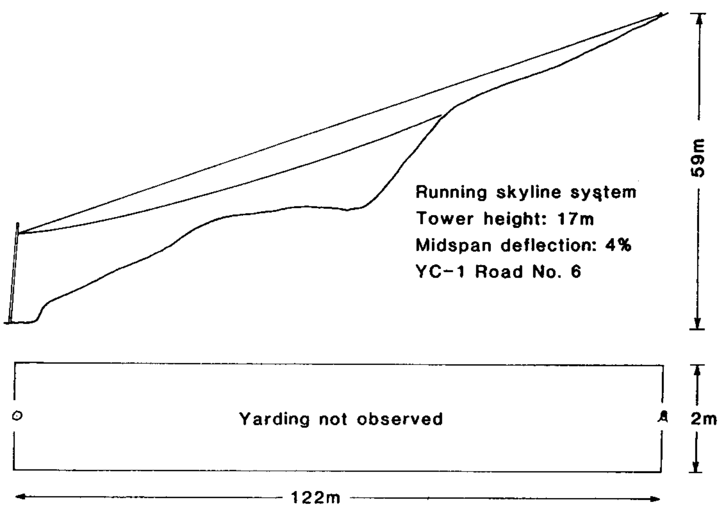
FIGURE 6: Examples of good yarding chances.



(a) Good yarding uphill perpendicular to contours.



(b) Fair to poor yarding across slope (parallel to contours).



(c) Poor yarding over generally convex slope and high road cutbank at landing.

FIGURE 7: Yarding chance varies as yarding progresses around a setting.

Settings with a fair chance for yarding (Figure 8) had a combination of features. Settings HL-7, YC-4, and SL-3 were downhill yarded on shallow chord angles with sufficient lift and deflection to avoid hangups. The skyline anchors on downhill-yarded SL-3 were well up the timbered hillslope and nearly half the skyline anchors on downhill-yarded SL-2 were placed well below the external yarding distance to maximize deflection. For half of the SL-2 area, the terrain was gently convex and deflection could not be improved by extending the tailhold. As well, the long distance required an extension to the skyline that resulted in production delays.

A poor yarding chance (Figure 9) primarily resulted when the yarder (HL-3, HL-4, HL-5, and HL-6) was forced to haul logs over a convex slope, with minimum or negative lift. The need to set the tower back from the landing edge so logs could be decked also reduced potential lift. In addition, production was reduced because distances were at the yarder's limit of line capacity (HL-1, Figure 9d). In these cases, the yarder mainline sheave, tailhold, and log load points were in a nearly straight line.

The limitations to yarding on the studied settings were determined by the existing setting layout and landing location. Production on HL-1 would have improved if the yarding distance had been shorter, but even at half to two-thirds the distance, lift was minimal and there were a number of oversized logs to be yarded. Highlead could have been used for SL-1 (Figure 6b) and SL-3 (Figure 8c), but the required full suspension of logs over a creek at about two-thirds the distance to the tailhold would not have been possible. If SL-2 had been highlead yarded, production would have been low because of the minimum lift and long yarding distance.

Yarding chance was not only variable over settings but also over the entire block. This was especially so at Study Site No. 6 (Figure 10). The yarding crane replaced the highlead yarder on the lower portions of the hillside because the crane could take advantage of the concave slope. Both yarders were forced to operate at their maximum distance, and at one point the crane was limited by line capacity. This reduced the necessity for construction of a mid-slope road, but yarder productivity was reduced. The highlead yarder yarded uphill over a convex slope. On these yarding roads, gouges (up to 1.5-m deep) were produced for two- to ten- m lengths.

Logs that were highlead yarded through gullies were difficult to control. They would slide down one gully side, sometimes overtaking the rigging. The log front-ends would dig into the gully channel and scrape the base of the adjacent gully side while being pulled into the landing. Logs would fall away from the cable path when being dragged along the sidewall rather than straight across.

The highlead scabline system (or simple running skyline) was successful in yarding uphill concave-shaped settings because the front-end of dragging logs could be lifted to clear stumps. With sufficient deflection and clearance, logs could be fully suspended.

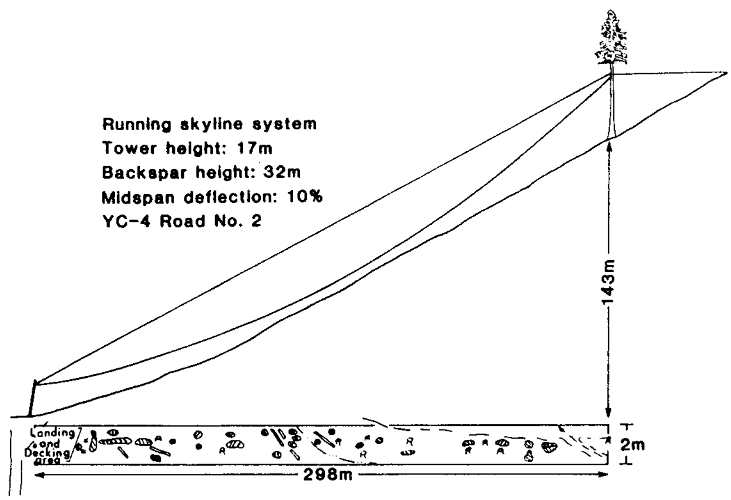
The scabline system could only provide lift when there was sufficient clearance for the haulback and mainline (usually at least 1 m) and for the chokers (2-3 m). The rigging would hang up on stumps and tangle if any less deflection was available.

The use of a skyline provided control over the inhauled logs, forcing the logs into the same path regardless of deflection or sideslope and concentrating disturbance. When there was minimal or no deflection, the carriage was prevented from reaching the tailhold. Logs and carriage would pass on opposite sides of stumps, resulting in hangups that were difficult to clear.

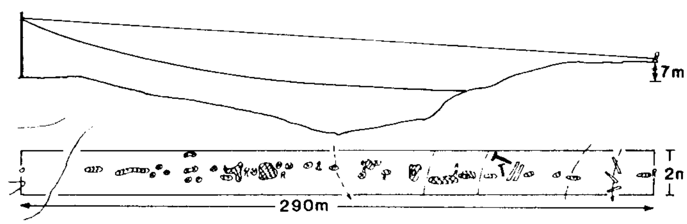
4.4.1.1 Landing and tailhold location

Landings can be located to improve logging chance, but are restricted by the existing road network. In Study Site No. 5, where most roads were pre-built, the crane (YC-3) could take advantage of the roads that encircled the setting to permit flexibility for yarding. When the adjoining settings were highlead yarded (HL-5 and HL-6), the road across the top of each narrow setting was so short that no flexibility for landing locations existed.

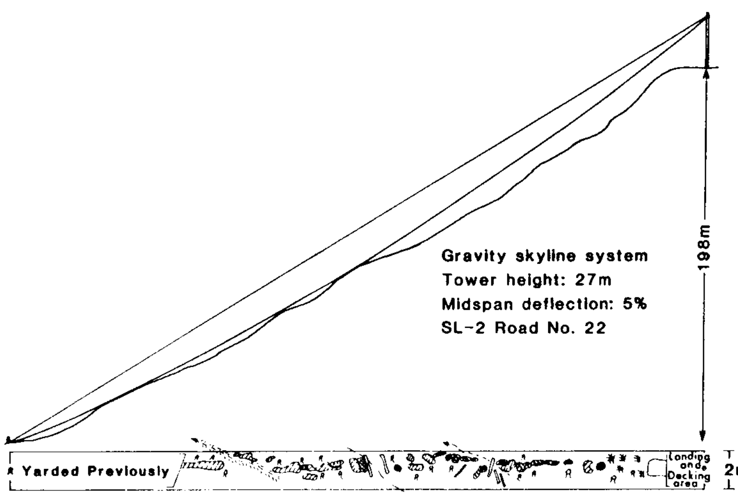
On Study Site No. 4, the highlead landings were not constructed until after the setting had been felled. This allowed better evaluation of the terrain than when the trees were standing, and ensured the landing location provided the best yarding chance.



(a) Backspar increased deflection at the back of the setting and allowed chokers to reach the tailhold without tangling. (Dropline carriage used.)

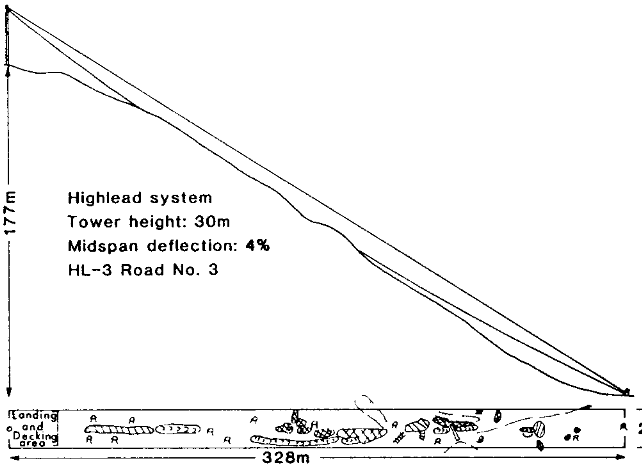


(b) Tower height and tailhold location created lift, especially at the midspan.

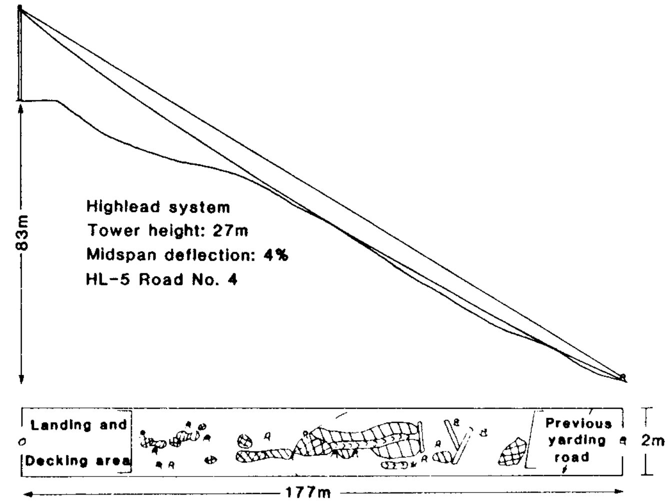


(c) Tailhold placed beyond the yarding boundary on a hillslope increased deflection.

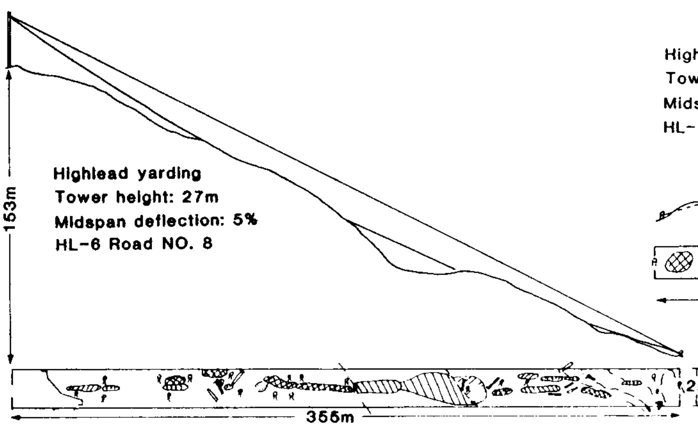
FIGURE 8: Fair yarding chance.



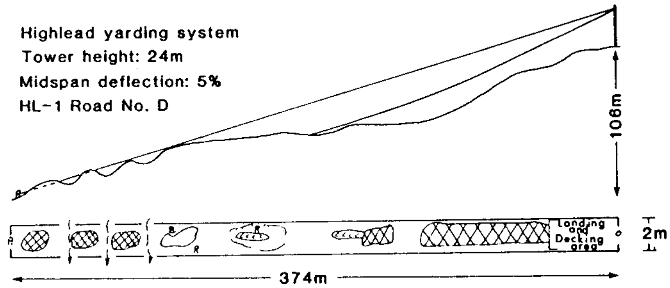
(a) Use of a step landing minimized reduced lift at the landing edge.



(b) Strongly convex shape reduced potential for lift.



(c) Convex and broken terrain caused by a gully reduced potential for lift.



(d) Long yarding distance decreased potential for lift.

FIGURE 9: Poor yarding chance.

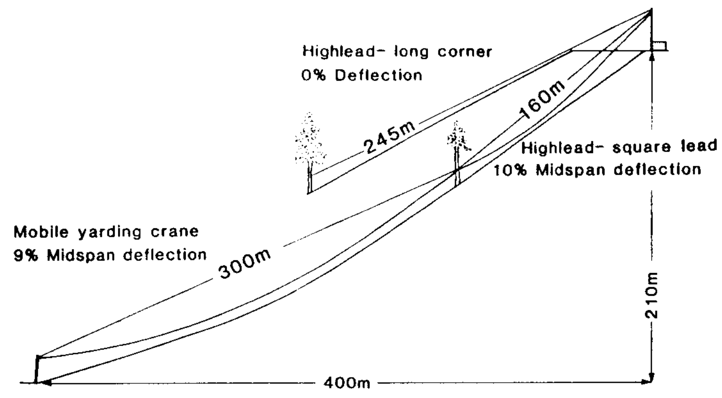


FIGURE 10: Yarding chance for Study Site No. 6.

Tailhold location is also critical to logging chance and is usually determined by yarder line capacity or the setting boundaries. On Study Site No. 6 (Figure 10) the boundary was placed for maximum yarding distance for the yarding crane. This resulted in poor conditions for the yarder on the road above. With skyline systems, the elevation of the tailhold may be increased by placing it beyond the setting boundaries. This is often very effective when the tailhold is located on a steeply rising bank across a creek (see Figures 6a and b). Deflection is not always increased when the tailhold is moved along a slope, because a longer span requires more cable sag.

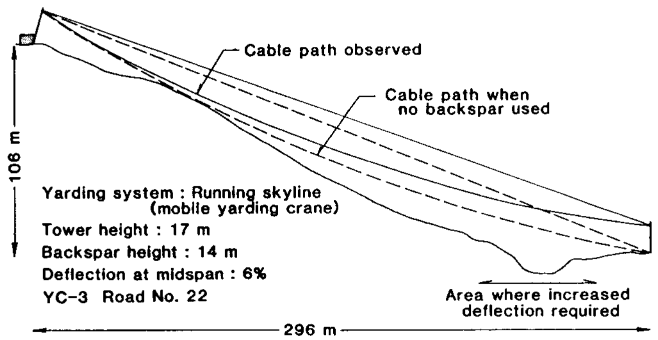
4.4.1.2 Backspars

Backspars may also improve logging chance by raising the tailblock to provide additional height at the back of the setting. They were used on several settings (YC-3, YC-4, HL-3, and HL-4). Standing trees, rather than mobile backspars, were used because the terrain was too steep and broken for mobile backspar access and use. Standing trees were rigged at 10 - to 15-m and 30 - to 35-m heights to provide for full suspension or to improve yarding efficiency by ensuring partial suspension. These spars require a skilled rigger and may require guylines. Although they are expensive to rig (one fully rigged backspar with two guylines took 6 hours to rig), they may provide the cheapest overall solution to yarding logs from a difficult area or where it is necessary to minimize disturbance.

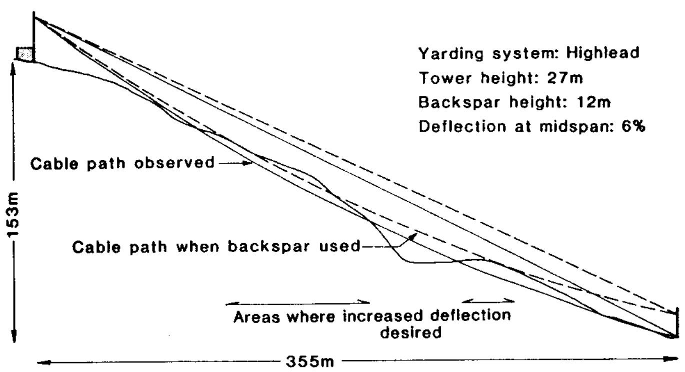
Backspars were effective in increasing deflection primarily at the back third of the setting (Figure 11). The longer the span, the less effect the backspar had at midspan. Generally, midspan ground clearance for highlead yarding roads over 250 m in length was increased sufficiently to allow the passage of the rigging, but not enough to increase the lift on inhauled turns significantly.

4.4.2 Number of logs passing over a point

Logs yarded on the same cable road usually travelled over the same ground. The alignment of the running lines determined the general path where disturbance would occur (2 -to 4-m widths) and terrain features such as stumps, depressions, and terrain outcrops tended to concentrate disturbance (1 -to 1.5-m widths). The greatest disturbance occurred in the first third of the yarding road and was related to the increased number of logs. Deflection was always greater than 9% and usually more than 12%.



(a) Mobile yarding crane.



(b) Highlead yarding with scabline modification.

FIGURE 11: Effect of high backspars on increasing deflection and yarding chance.

The number of logs that are inhauled along a road is determined by the stand density, the length of the yarding road, the width of the yarding road, and the height of the trees (number of logs per tree). Table 11 shows that between 2 and 23 times more logs cross a point 50 m from the landing than those crossing the last 50-m yarding interval at the tailhold.

The wider cable road spacing and longer yarding distances on skyline systems resulted in more logs over the same ground and more disturbance in the front of the setting. Grapple-yarded roads tended to be narrower than choker-logged roads and the number of logs on each road was less than for the highlead or skyline system. These factors contributed to the low yarding disturbance on crane-yarded settings, especially at the front of these settings.

During the gully yarding studies it was apparent that gully location with respect to the landing contributed to the amount of disturbance. There were generally only a few logs lying on the gully sidewalls or in the channel. In a gully located at the back of the setting, often just the sidewall nearest the landing and the channel were lightly disturbed because only a few logs were yarded from beyond the gully. Gullies that were located at the front or in the middle of the setting often had both sidewalls and both edges severely disturbed by the considerable number of logs yarded from beyond the gully. Impacts on gullies may be reduced by such measures as leaving old stable debris undisturbed and locating yarding roads so they utilize the maximum available clearance

TABLE 11. Number of logs crossing the same point on sample yarding road

System	Yarding road	Horizontal distance (m)					
		50	100	150	200	250	350
		Number of logs crossing					
Highlead	HL-1	44	44	44	41	22	6
	HL-2	116	82	56			
	HL-3	76	76	67	51	31	9
Yarding Crane	YC-2	45	21	9			
	YC-2	17	17	13	8		
	YC-3	116	109	84	74	49	5
Skyline	SL-2	123	118	99	79	46	10

while minimizing yarding along the gully sidewall. Depending on the topography, clearance can be maximized by yarding parallel or perpendicular to the gully (Figure 12).

Even when logs were fully suspended over a gully, disturbance could occur at the point where the logs touched down (Figure 6b).

4.4.3 Log sizes and weight

Heavy, short logs were difficult to yard because their front-ends were difficult to raise. Disturbance resulted because these pieces dug into the ground during yarding. Also, disturbance occurred when average weight, long logs (15 - to 20-m long) had to be yarded and deflection was inadequate.

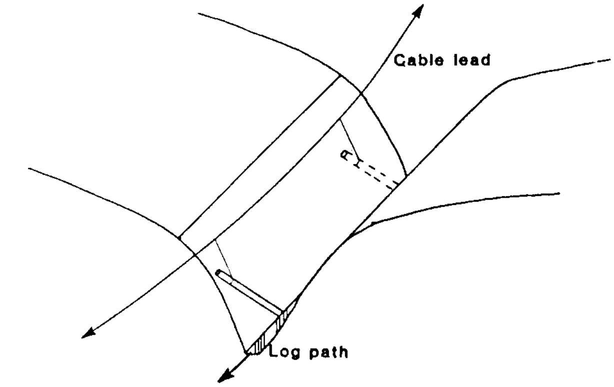
Downhill-yarded large logs rolled or pushed against stumps. Substantial shock loads occurred as these logs left the ground and swung wildly when fully suspended. This caused disturbance to the ground and to stumps, and was damaging to lines and equipment. Uphill-yarded oversize, overweight logs dragged along the ground, plowing the upper litter soil layer and digging into the mineral soil. Obstructions encountered when yarding large logs often caused hangups that resulted in delays and inefficiency.

Most logs were less than 12 m long, although trees that could not be bucked for safety reasons sometimes exceeded 25 m. These long logs caused disturbances similar to those of large logs, and full suspension was usually not possible. In order to fully suspend a 25-m long log on a 250-m horizontal span with 5% deflection, a total of 42.5 m (127 ft) of clearance is required (assuming a 5-m choker length). This clearance is not usually available.

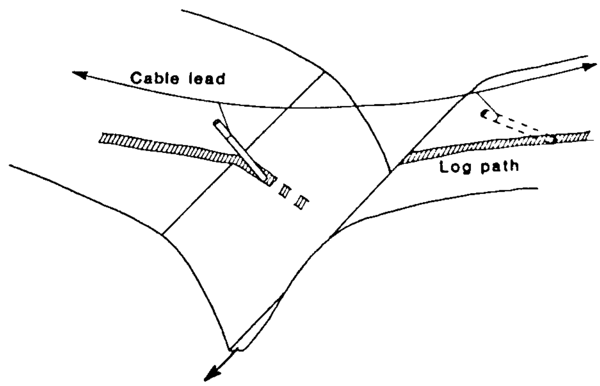
4.4.4 Distance from carriage to log attachment and position of choker on log

The chokers used during highlead and skyline yarding were 5-9 m long and usually satisfactory for partial suspension. When logs were too far off the cable path to be reached with one choker, two chokers were joined together. This could result in the log being dragged without any suspension the full length of the road. The extra choker length decreased the angle available to lift the log, made breakout difficult, and reduced control of downhill-yarded logs. Sometimes the crew stopped the yarder and re-attached a single choker, which resulted in a delay of 3-8 minutes.

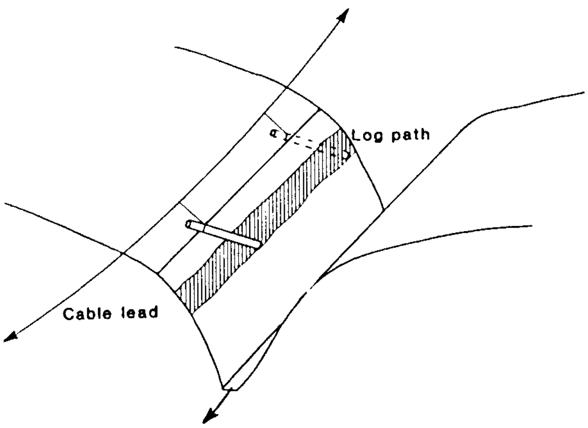
The shortest attachment was the grapple (1 m); however, this distance would increase 10-14 times when a choker or double chokers were used to attach logs beyond the reach of the grapple. One yarding engineer grappled the choked log when it was within reach to minimize yarding difficulties.



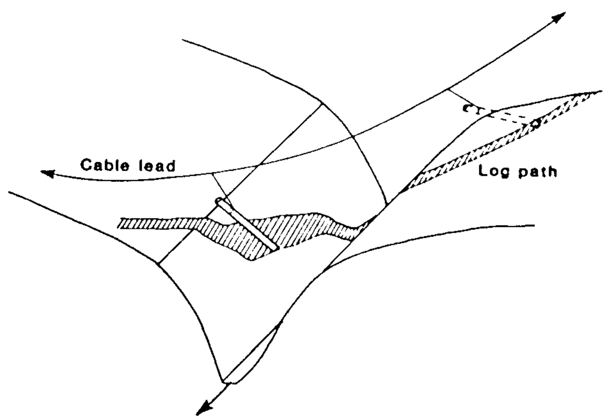
Yarding parallel to gully.



Yarding perpendicular to gully.



Yarding along gully sidewall.



Yarding diagonally across gully.

FIGURE 12: Gully yarding techniques.

When logs were choked or grappled near their end, inhaul was uneventful. Logs that were attached at mid-length or near their centre of gravity would swing when fully suspended. During inhaul, these logs would continue to swing and sometimes strike the ground and stumps with considerable impact.

4.4.5 Yarding direction

Logs yarded uphill with their fronts just clearing the stumps appeared to glide over the ground, and slash protected the ground from disturbance. As the angle of pull to the log decreased, the log would be dragged into stumps. Uphill-yarded logs stayed in a relatively narrow track during inhaul.

If the angle of the log to the ground during downhill yarding was too low, the log would slide and run into stumps, resulting in hangups. To free them, the logs were rechoked or the stump was pulled out.

During downhill yarding, the log weight not carried by the choker was concentrated on the log end. In study area YC-4, the dragging log ends caused the water running below the surface litter layer to appear on the surface. Disturbance was concentrated at the foot of debris lying across the slope and was caused by the log ends bouncing off the debris. The bouncing log ends also disturbed fine-textured, moist soils within local depressions.

The yarding path for downhill yarding appeared wider than for uphill yarding because logs tended to zigzag during inhaul as they were deflected by stumps, depressions, or mounds.

Nowhere in the study was it observed that downhill yarding concentrated surface or subsurface water flow to a central landing. In all cases where yarding roads interrupted surface flow, the water was channelled into other surface drainages within 2-3 m.

Logs yarded parallel to the contours tended to roll downhill and created yarding difficulty. The tendency for logs to roll away from the cable path resulted in wider areas of disturbance. When rock outcrops were encountered, the log end slid and dragged along the slope completely removing the surface cover and surficial soil layers. Stumps that interfered with inhauled turns were often pulled out to reduce hangups of subsequent turns.

4.4.6 Yarding pattern

Two distinctive yarding patterns result from variations in yarder and tailhold locations. If the yarder was stationary and the tailhold moved around the setting, a radial pattern was produced. If the yarder and tailhold were moved for each yarding road, a parallel pattern resulted.

Radial skyline patterns with wide road spacing should reduce disturbance to sensitive areas because of the wider areas left undisturbed between roads. The skyline is placed in a position to maximize lift, and areas of sensitivity are then avoided by turns being fully suspended over them. Highlead yarding roads cannot avoid sensitive areas. However, from the observations in this study, the widely spaced skyline roads were much more visible and disturbance was concentrated to localized areas where a large number of log ends were dragged along the ground. The disturbance events along skyline yarding roads appeared to be of a deeper and generally more destructive nature than corresponding disturbance on similar highlead yarding roads, where only the surface of the mineral soil layer was usually disturbed.

Skyline yarding roads 50-70 m apart required up to 35 m of lateral yarding. Disturbance (primarily pulled stumps) from lateral yarding increased as skyline ground clearance decreased and was widely scattered.

The parallel pattern of the yarding cranes produced the least visible yarding disturbance. Residue was left in place and disturbance was restricted to areas of hangups, poor deflection, or soft, wet soil.

4.4.7 Yarding speed

Logs inhauled at normal speed were easier to control than those inhauled at high speed. Normal inhaul allowed the log to follow the ground and the lines could be stopped quickly when an obstacle was encountered. As inhaul speed increased, momentum of the log also increased. At high speed, this resulted in high impact loads when log ends struck the ground or stumps. The best speed appeared to be just fast enough to keep the log moving smoothly.

4.4.8 Full suspension

Cable-yarding systems that can fully suspend turns have been consistently recommended to reduce yarding disturbance and minimize slope movements. Full suspension using cable systems requires sufficient ground clearance, deflection, and a yarder system that can provide the lift. The potential for full suspension on a yarding road can be evaluated by plotting a profile of the yarding road and examining the distance between the chord slope and the ground. This distance must be greater than the longest log and choker length, plus an amount equal to the required deflection. (In this study, 5-9% of the horizontal span was used.)

During these investigations, full suspension occurred on five settings. Disturbance was concentrated at the point where the logs increased their lead angle before suspension and as the log ends touched down again before the landing. When the log lift-off point was close to a stream or gully, the swinging log end would scrape away debris from the ground and sweep it downslope. This increased the debris in the channel or along the base of the sidehill (Figure 13).

Full suspension appeared to be most effective when located at the back half–especially at the last third–of the yarding road. At these positions the yarder winch has the maximum line pull and there are fewer logs to yard.

4.4.9 Yarding disturbance to gullies

There was no evidence found during initial data collection and the two- to three-year period following yarding that the amount of debris left in the upper reaches of gullies contributed to failure initiation. The majority of debris accumulations were a result of falling large trees on long gully sidewalls where directional felling was not possible. Debris also seemed to accumulate in gullies regardless of the yarding direction. The least yarding debris accumulated when logs had been yarded in full suspension for 50-75 m before the gully, allowing loose branches to fall-off on the hillslope. The greatest yarding debris accumulated when logs dragged slash from the gully sidewall into the gully bottom or debris dropped off logs as logs crossed the channels

No attempt was made to clean debris out of the gullies logged. Although the overall bulk of debris in Study Sites Nos. 5 and 6 was high, the debris appeared to consolidate in 2-3 years after logging. This was probably because of the small woody branches drying, becoming brittle, and breaking from snow weight or wind.

In some areas where logs had been yarded from or along gullies, old logs and windfalls stabilizing the channel were dislodged and created potential areas of local instability.

4.4.10 Anchors

Guyline and tailhold anchors were continually subjected to impact loads from the yarding. One haulback anchor failure was observed. This occurred when a stump group of second-growth timber located above a previous revegetated landslide gave way. The hooker had recognized the location as a potential problem and immediately stopped the yarding when failure occurred. (The dislocated root mass has remained in place.)

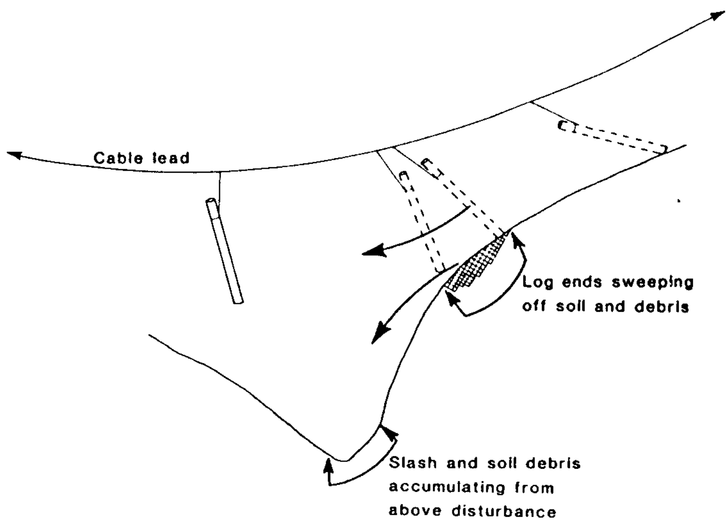


FIGURE 13: Yarding disturbance caused at lift-off points prior to full suspension (SL-3).

The impact loads on guyline stumps could be substantial. As an example, one guyline with a breaking strength of 711 000 N broke.

4.4.11 Landings

Landing areas located above gully headwalls were particulary difficult for log decking. These landings were located as far into the gully as possible (to provide long-distance yarding) without causing sidecast or headwall disturbance. Deflection was reduced at the landing because the yarder was usually located away from the edge to allow the log loader to deck logs.

Several split landings were constructed to provide increased tower heights and good decking areas. The largest landing was constructed for a highlead setting and a front-end loader.

Throughout the study, loader operators were observed pulling stumps to provide more area for log storage. These stumps, as well as landing debris, were usually thrown downhill and sometimes into a gully channel or into the gully headwall.

The lengths of landing disturbance (the landing and the area where logs were decked or stored) associated with yarding roads are summarized in Table 12. Highlead landing disturbance occurred because logs slid down steep hillsides after unchoking and prior to being loaded on a truck. Decking areas at yarding-crane settings were generally flat or the yarder decked wood on the road if the side slope was too steep to hold logs. The length of disturbance on yarding-crane roads was related to the distance the yarder was set back from the log deck or by the length of yarded logs. Skyline landing disturbance was generally less because landings and decking areas were small and a loader retrieved the logs immediately after unchoking. The adjusted landing disturbance reflects the effect or road density and indicates that highlead has a higher amount of area associated with landing disturbance, and skylines substantially less.

Table 12. Landing disturbance

System	Study	No. of roads	Length of landing disturbance along yarding road			Adjusted landing disturbance (m)
			Minimum (m)	Maximum (m)	Average (m)	
Highlead	HL-1	1	42	42	42	193
	HL-2	5	27	56	39	200
	HL-3	3	27	37	30	385
	HL-4	4	32	53	41	204
	HL-5	6	26	40	33	169
	HL-6	4	24	27	25	111
	HL-7	1	40	40	40	154
Mobile Yarding Crane	YC-1	5	21	31	28	114
	YC-2	5	23	30	27	147
	YC-2a	1	30	30	30	121
	YC-3	13	13	33	24	96
	YC-4	7	11	24	16	25
Skyline	SL-1	1	55	55	55	72
	SL-2	23	15	3	23	83
	SL-3	2	27	31	29	17

It was observed that when a landing was small, a loader was needed continually to move logs away from the yarder.

Small logs, bucked ends, and tops accumulated around the landing. Ditches through landings and along crane-yarded areas were piled with debris and logging slash especially during downhill yarding. Ditches adjacent to active landings should be cleared regularly by the loader during logging.

4.4.12 Supervision, crew size, and attitude

Yarding production and disturbance appeared to be related to management enthusiasm and crew size. Production improved and disturbance was reduced when:

- the management and crew had a clear understanding of what was required; and
- the desired results were practical and achievable.

Co-operation from all members of the crew was vital, and communication was easiest with smaller crews. The on-site supervisor seemed to be the key to effective yarding. He had the authority to balance production with yarding results.

Yarding results were also related to how experienced the crew was with the particular system. When an efficient grapple operation was changed over to an unfamiliar dropline system, productivity suffered. The crew were dissatisfied and only wanted to finish the job as quickly as possible.

It became apparent during this study that yarding disturbance can only be avoided if everyone in the overall operation can do his job well. Roads and landings must be located and constructed to provide sufficient lift or deflection. Trees should be felled in a direction that assists yarding and bucked to minimize long and overweight logs. Landings must be large enough to provide room to work and to store debris.

4.5 Other Disturbance Observed

4.5.1 Falling disturbance

The over-mature, large trees that grow throughout the Queen Charlotte Islands are often hazardous to fell and difficult to fell directionally because of their large branches and excessive rot. Although no quantitative data were collected to show the extent of falling disturbance, it was obvious during the reconnaissance of felled settings. Felling disturbance occurred if tree butts hit the ground and exposed small patches of mineral soil. Gouging occurred if trees slid down a hill. Occasionally, sliding trees even up-rooted stumps and exposed rock outcrops. Felled trees also tended to accumulate in gullies.

4.5.2 Loss in vegetation

There appeared to be changes in micro-climate between the logged and unlogged terrain. During two winters of evaluation, the soil on open slope–and especially within gullies–was observed to be frozen during periods of cold ($0^\circ$to -10° C air temperature), whereas the adjacent timbered slopes showed no sign of frozen ground. Extensive areas of thick moss on logged gullies were often lifted out of the ground by ice crystals. When the ice melted, the moss fell off the steeper slopes.

Ground vegetation within gullies also dried out during the period of summer heat, while the shaded forested gullies usually remained damp.

These changes to the micro-climate may reduce the amount of surface vegetation along gully sidewalls and increase soil ravelling into the channel.

4.6 Slope Failures Observed During the Study

Twenty-three slope failures were observed on or near the study areas and occurred during or within 2 years of logging (Table 13). All of the settings had portions of their areas that had signs of instability: slopes over 70 percent (35°); excess water at times; infilled depressions; and historic failures. Seven of these failures, including the five largest failures, could not be associated with yarding. The four largest failures occurred after felling and had evidence to suggest that redirected road drainage may have been a contributing factor (Krag *et al.* 1986). The fifth largest and two smaller failures occurred in forested control areas.

TABLE 13. Summary of failures in the study area

Failure no.	Date of falling	Study site	Date of logging	Type of failure	Date of failure	Est. volume (m^3)	Length (m)	Width (m)	Approx. area (m^2)
Failures that occurred after felling and prior to yarding									
3	Summer '83	5	Aug. '84	Torrent	Aug. '84	1100	550	8	4400
8	Spring '83	6	Oct. '83	Flow	Aug. '83	1000	200	20	4000
9	Spring '83	6	Oct. '83	Flow	Aug. '83	900	250	15	3800
10	Spring '83	6	Oct. '83	Flow	Aug. '83	1500	400	15	6000
Failures that occurred during yarding									
1	Summer '80	1	Aug. '81	Flow	Aug. '81	5	5	2	10
Failures that occurred after yarding									
2	Summer '80	2	Oct. '81	Flow	Oct. '81	20	10	5	50
4	Spring '83	5	Aug. '83	Slide	Nov. '84[a]	10	10	5	50
5	Spring '83	5	Aug. '83	Flow	Nov. '84[a]	10	8	3	24
11	Spring '83	6	June '84	Slide	Nov. '84[a]	20	17	5	85
12	Spring '83	6	June '84	Slide	Nov. '84[a]	20	12	8	96
13	Spring '83	6	Oct. '83	Slide	Nov. '84[a]	10	10	5	50
14	Spring '83	6	June '83	Flow	Nov. '84[a]	40	15	5	75
21	Winter '83	7	July '83	Flow	June '84[a]	15	15	5	75
22	Spring '83	5	Aug. '84	Flow	Feb. '86	5	5	2	10
23	Spring '83	5	Aug. '84	Flow	Feb. '86	20	15	4	60
Failures that occurred after yarding on portions of settings where yarding was not observed									
15	Spring '83	6	Aug. '83	Slide	Nov. '84[a]	15	18	3	54
16	Spring '83	6	June '83	Slide	Nov. '84[a]	5	8	3	24
17	Spring '83	6	May '83	Slide	Nov. '84[a]	20	12	5	60
16	Summer '84	6	Aug. '84	Flow	Nov. '84[a]	600	110	10	1100
19	Spring '84	6	July '84	Flow	Nov. '84[a]	70	55	5	275
Failures that occurred on control gullies adjacent to yarding									
6	Summer '82	5	Oct. '83	Flow	Jan. '84	80	40	8	320
7		5		Flow	Jan. '84	50	30	7	210
20		6		Torrent	Aug. '83	600	425	6	2550

[a]Date of failure unknown–this is date of first noting.

Table 14 summarizes the factors and terrain features noted at each failure. Sixteen failures were associated with yarding. Of these, 14 were less than 100 m^2 in area. Most of the yarding failures were associated with periods of heavy rainfall.

Thirteen of the yarding failures were located within gullies and two were within localized infilled depressions in the headwall.

TABLE 14. Summary of failure characteristics

			Associated disturbance						Conditions at time of failure				Associated terrain feature						
Failure no.	Setting no.	Yarding system	Scraping	Mineral soil exposed	Rock exposed	Gouging	Disturbance within depression	Dislocated/ uprooted stumps	Rain	Standing timber	Windfall	Excess water	Gully Edge	Gully Wall	Gully Headwall	Open slope	Debris entered channel[b]	Open slope to gully	Road
Failures that occurred after felling and before yarding																			
3	5								X			X	X		X		X[1 b]		X
8	3								X		X	X				X		X	?
9	6								X		X	X				X		X	?
10	6								X		X	X				X		?	
Probable yarding-associated failures																			
Failures that occurred during yarding																			
1	1	HL	X	X	X				X			X	X						
Failures that occurred after yarding																			
2	2	HL	X	X				X	X			X	X				X		
4	5	YC	X	X					?			?		X					
5	5	YC						?	?			X		X					
11	6	HL	X	X				X	?			?		X					
12	6	HL	X	X	X				?			?		X					
13	6	YC							?			?		X					
14	6	YC						X	?			X			X				
21	7	SL	X	X	X				?			X			X				
22	5	HL	X	X		X			?			X			X	X			
23	5	HL					?[a]	?	?							X			
Failures that occurred after yarding on portions of settings where yarding was not observed																			
15	6						X	X	?						X				
16	6								?					X					
17	6						X	X	?						X				
18	6						X	?	?			X				X			
19	6							?	?		X	X			X		X[2]		
Failures that occurred on control gullies adjacent to yarding																			
6	5								X	X							X		
7	5							?	X			?			X		X		X
20	6								X	X	X	X		X			X[1]		

[a] No clear relationship but evidence exists to indicate a probability that factor was involved in failure initiation.
[b] X[1]-travelled along channel short distance; X[2]-travelled along channel more than 100 m.

Two of the 16 failures had no evidence of disturbance in their initiation zones. These were associated with old gully wall failures.

Stump dislocation appeared to be the sole factor in three failures, and a contributing factor in six more. Four failures were associated with disturbance to depression areas, in combination with dislocated stumps. One failure was associated with scraping and mineral soil exposure. Six failures were associated with combinations of three disturbance forms: mineral soil exposure; gouging; and dislocated stumps.

4.6.1 Yarding-associated failures and disturbance.

During the period of our study (1981 - 1984), there was no obvious relationship between the proportion of yarding road disturbed and the number of failures that occurred on the setting (Table 15). Highlead did have the greatest amount of disturbance, however, the mobile yarding crane had 14 percent less disturbance and nearly half the failure frequencies for all failures and large failures.

While it would seem logical that increased disturbance would result in more failures, this was not clearly demonstrated in the time period of this study. The study does demonstrate that potential failure-initiating sites are localized and small, that yarding disturbance is probably only one of several factors in the initiation of landslides that occur within two years of yarding, and that disturbance to non-sensitive sites is probably not important. If yarding disturbance alone is to initiate a slope failure, it must occur at a specific area where the slope is greater than 31° (60 percent), there is a source for concentrating water, the soil conditions favour failures, and there is a heavy windfall. The greater the yarding disturbance on a steep sensitive setting, the greater the chance for a yarding-induced failure. The less the disturbance, the less chance for yarding disturbance to coincide with a sensitive area.

4.6.2 Failure frequency

Table 15 also shows the frequency of failures per square kilometre per year. All failures that occurred after yarding are included, whether or not yarding disturbance was present. Because the total study area is small (1.065 km^2), caution must be used when extrapolating these data. On Study Site No. 2, the one failure resulted in 37.0 failures per km^2 or 5.7 failures per km^2 per year when the time since timber cutting was considered.

All failures occurred on local slopes greater than 58 percent (30°), however, the general slope over the settings varied. The high failure frequencies that occurred on Study Site Nos. 5, 6, and 7 were probably the direct result of their large areas with over 60 percent (31°) slope compared to other areas, and the occurrence of storms that struck the settings before and shortly after yarding in August 1983 and January 1984. These settings had longer continual slopes over 55 percent (29°) compared to the other areas. The failure on HL-2 occurred on a gully wall with average slopes of 90 percent (42°).

A greater number of logs crossed over steep gully walls on HL-1 compared to SL-1 and probably contributed to the failure initiation. Weather conditions during yarding were similar. The general slope on YC-3 was not as steep as HL-5 and HL-6, resulting in less potential for failure.

The areas where no failures occurred had local areas of over 60 percent (31°) slope, however, there were larger areas of reduced slope created by undulating and rolling terrain. Bedrock was more visible on SL-2 than on other settings and probably demonstrates the controlling nature bedrock has in assisting soil stability. The large area with slope over 50 percent (27°) on SL-2 made it similar to HL-3, HL-4, HL-5 and HL-6, however, no large failures occurred.

Even though the sample is small, the results may be compared to a FFIP study undertaken to determine the effect logging has on accelerating landslide activity (Rood 1984). Rood only identified failures over 200 m^2 in area to avoid missing small failures hidden by the forest canopy. He determined that 3.6 failures (over 200 m^2 in area) per km^2 per year were associated with

TABLE 15. Yarding disturbance and area failure frequency

Study site	Yarding study	Total area logged (km^2)	% of yarding road disturbed per km^2 logged[a]			All failures ($10—6000\ m^2$)		Large failures only (over $200\ m^2$)		Time period[b] (yr.)
			Shallow	Deep	Total	No.	Frequency[c]	No.	Frequency[c]	
1	HL-1	.037		51	51	1	4.3	0	0	6.3
	SL-1	.036	19		19	0	0	0	0	6.3
		.073	4	39	43	1	2.2	0	0	6.3
2	HL-2	.027		23	23	1	5.7	0	0	6.5
3	YC-1	.029	9	15	24	0	0	0	0	5.9
4	YC-2	.080	12	13	25	0	0	0	0	5.3
5	YC-3	.108	5	14	19	2	5.3	0	0	3.5
	HL-5 & 6	.085	13	33	46	2	6.7	0	0	3.5
		.193	11	28	39	4	7.4	0	0	3.5[d]
6	YC-4	.404	5	14	19	1	1.0	1	1.0	2.5
						4	2.8			3.5
	HL-3 & 4	.117	13	26	39	4	9.8	1	2.4	3.5
		.521	3	25	38	9	5.1	2	1.1	3.4[d]
7	SL-2	.068	20	23	43	1	5.4	0	0	2.7[e]
8	SL-3	.048	6	32	38	0	0	0	0	2.0[e]
	HL-7	.026	3	31	34	0	0	0	0	2.0[e]
		.074	4	31	35	0	0	0	0	2.0[d]
	Highlead	.292	9	29	38	8	6.8	1	0.9	4.0[d]
	Yarding Crane	.621	7	13	20	7	3.2	1	0.5	3.5[d]
	Skyline	.152	19	22	41	1	2.0	0	0	3.3[d]
	Total	1.065	11	23	34	16	4.2	2	0.5	3.6[d]

[a] Length of disturbance per ha x 100/length of yarding road per ha (Table 10).
[b] Time in years from falling to last observation date (November, 1986).
[c] Number of failures per km^2 of logged area per year since falling.
[d] Weighted average (area and time period).
[e] Last observation date October, 1985.

clearcuts, and 4.1 with clearcuts and roads. This study indicates 0.5 failures (over 200 m^2 area) per km^2 per year are associated with yarding (two failures during 3.6 years), and 1.4 failures per km^2 were associated with yarding and roads (six failures during our four-year study).

This difference may be the result of changes that have occurred in yarding system usage and layout. Rood's study examined areas logged during the period 1964-1981, whereas this study covered settings logged between 1981 and 1984. During this period, loggers on the Queen Charlottes used the yarding cranes to log some areas that would have been highlead yarded in prior years. Layout may also have improved because terrain specialists now identify specific areas of instability. In addition, areas with indications of extreme instability, which may have been logged in the early 1970's, may not now be approved for logging.

The difference between Rood's study and this one also suggests the potential role of root deterioration. If the number of failures continue to increase to Rood's level, then it is more likely that the loss of root strength and the recurrence of storms are the major factors contributing to landslide initiation on logged areas. Yarding disturbance may be a secondary factor because the root network has been disturbed or is exposed to increased rates of weathering and decay.

5 CHARACTERISTICS OF SENSITIVE SITE

Although detailed assessments of terrain stability were not undertaken, each setting showed specific evidence of potential sensitivity.

The following indicators of localized sensitivity were noted on open-slope portions of the settings observed on the Queen Charlotte Islands:

- linear depressions along the slope or bowls on concave slopes that had more moisture relative to the surrounding area. The soil was usually finer textured and deeper than on the adjacent slope, and the vegetation lusher.
- evidence of historic revegetated landslides or more recent failures with little or no vegetation. This may indicate that the most sensitive areas have already failed and that adjacent areas may be stable if located on different terrain units.
- thin layers (less than 20 cm deep) of wet high-organic content soils (folisols) over bedrock or compacted glacial till on slopes over 60-65% (31-33°).
- water seeping out of the ground and puddling during wet weather; and saturated slopes of colluvial or old slide-deposited material that turned quickly to mud when disturbed.

The site indicators were visible before tree felling and during yarding, but were often obscured by the felled timber before yarding. The shape of the terrain, shallow drainage patterns, and linear depressions were often visible on felled settings when viewed from a distance. Yarding crews can use these signs of potential instability to avoid having yarding roads located on sensitive sites.

Gullies on the Queen Charlotte Islands are recognized by terrain specialists as being sensitive sites and have a high probability for failure. Two of the study gullies had evidence to suggest they had failed within the past 10 years. In addition, the gullies had:

- numerous examples of old and recent landslides along their sidewalls;
- natural accumulations of logs that held in-channel gravels, sediment, and sidewall material;
- steep gully sidewalls (often over 100% (45°) slope) with some slope lengths exceeding 100 m, although most were between 15 and 30 m;
- extensive mats of shallow root webs across the vegetated slopes and
- localized areas of concentrated drainage. Some of these were infilled depressions that concentrated moisture in funnel-shaped basins immediately above the gully edge.

6 SUMMARY, RECOMMENDATIONS, AND CONCLUSIONS

Fourteen yarding settings on eight different sites on the Queen Charlotte Islands were monitored to measure productivity and evaluate logging system effectiveness, to document yarding disturbance, and to determine how disturbance may contribute to landslide initiation.

The two systems in common use on the Queen Charlotte Islands are the portable steel spar using the highlead or modified highlead (scabline) system, and the mobile yarding crane using a grapple or chokers. These systems achieve similar productivity (200-300 m^3 per 8-hour shift), but highlead costs ($5.60-$12.90/m^3) are higher than yarding-crane costs ($5.65-$9.70/m^3). Highlead and yarding cranes complement each other on sites with different characteristics. Highlead with its tall spar is the best system for logging very steep convex slopes where the logs must be yarded to a central landing. It is the only system that can be used with no deflection. Mobile yarding cranes work best when they can use their mobility and swing capability to deck logs along a roadside. The mobility and swing of the boom can also be used to direct the logs along yarding roads to reduce hangups and minimize disturbance.

Skyline systems are used in areas where it is necessary to increase yarding distance. These systems do not necessarily reduce yarding disturbance, but may eliminate the need for building truck roads through sensitive areas. Skylines also offer the potential to suspend logs fully over sensitive terrain. Skyline systems are more expensive than yarding cranes or highlead, ($9.20 to $29.00/$m^3$), and are more complex to operate. They require a skilled dedicated crew and are more subject to breakdowns.

It was obvious in our field studies that limitations of existing yarding systems were more related to the application of the system rather than to the capability of the system.

Twenty-three slope failures occurred on or near the studied areas. Seven of these failures (all over 200 m^2 area) were not associated with yarding (four occurred before yarding and were probably road drainage associated and three occurred on non-logged control areas). The study confirms the importance of good road location, road construction, and road maintenance in reducing the overall occurrence of logging (yarding and road-associated) failures.

Mass wasting on open slopes following logging on the Queen Charlotte Islands and elsewhere is the result of a combination of interacting factors, including slope, soil moisture, soil properties, bedrock geology, and deterioration of root strength. The most critical slide initiation factor from the literature and from our observations appeared to be an increase in soil moisture during periods of heavy rain. Nineteen (83%) of the twenty-three failures recorded occurred following a major storm in 1984. Natural stability may also be reduced because of changes in the micro-climate due to tree removal.

Although no quantitative data were collected, the falling process can cause disturbance if mineral soil is exposed, gouging occurs, or stumps are uprooted when the trees are felled.

Ground disturbance and productivity are directly related to logging chance. When logging chance was poor, disturbance was high and production low. When the chance was good, disturbance was minimal and production good.

Backspars can be used to increase lift at the back of any setting, but have little effect at the centre or front. High backspars are expensive to rig and require a skilled crew.

There was little observed difference in productivity or disturbance between uphill and downhill yarding, but in the sites we observed, cross-hill yarding on slopes was less productive and increased disturbance. There was no evidence of water concentrating at landings after downhill yarding. Debris tended to accumulate in gullies during all yarding and at landings and in ditches during downhill yarding.

Large-diameter overweight logs and long logs caused more disturbance than average-size logs. Logs hooked in the centre or choked with two chokers (tagged) often caused disturbance.

Disturbance increased with the number of logs yarded over the same ground, therefore disturbance was more severe near the landing, on settings with long yarding distances, and on wide-spaced skyline roads.

Sixteen failures occurred following yarding and two were over 200 m^2 in area. Fourteen of these failures were associated with some form of observed yarding disturbance, and two failures were associated with steep gully walls and reactivated historic slope movements.

Yarding disturbance can contribute to slope failure initiation by altering the flow of surface and subsurface water and by removing the reinforcing strength provided by the roots of uprooted and dislocated stumps. Yarding disturbance alone could not be attributed to the initiation of any slope failure that occurred after logging on our study sites. However, yarding disturbance was probably a contributing factor in sixteen post-yarding failures by reducing the threshold of stability. There was no obvious relationship between slope failure initiation and the amount of yarding disturbance.

The overall yarding and road failure frequency (failures per square kilometre logged per year) during the study (1.4 failures over 200 m^2 area per km^2 per year) and the yarding failure frequency (0.5) were much less than those observed by Rood in a related FFIP study (4.1 failures over 200 m^2 area per km^2 per year for clearcut and road, and 3.6 for clearcut failures). This may reflect changes in logging methods or the climate in recent years, or indicate that the period of observation in this study was too short. If slide frequency continues to increase on the study areas, it will indicate that root deterioration is probably an important contributing factor. An increase may also be due to new surface run-off patterns developing that direct surface water to localized sensitive sites. In any case, the study settings should be monitored over time and any future slides documented.

Sites with the greatest potential for failure are on slopes over 60 percent (31°), with thin, high organic content soils over rock or hardpan; are in shallow linear depressions; or are within gullies having evidence of previous failures and long steep sidewalls. Most of these sites are noticeably wet or support moisture-loving vegetation. Although the shape of the ground may be easier to visualize after felling, the on-the-ground site indicators may be obscured by the logs.

6.1 Recommendations

1. Identify sensitive sites before roads and settings are laid out, and keep plans flexible enough to benefit from additional information as it becomes available.
2. Identify gullies and treat them as sensitive sites. Where practical, use gullies as setting boundaries and cut all the trees on both sides which may fall into the gully when the first side is logged. This will minimize the number of logs dragged across gullies so the potential for disturbance to initiate a failure is reduced and will minimize the accumulation of yarding debris in the channel.
3. Consider the location of oversized logs when planning the yarding operation and not just the average-sized logs. Try and minimize the yarding distance of oversized logs and avoid having them yarded across gullies.
4. Plan truck road location, choice of yarding system, and setting layout together. Plan the logging of all adjacent timber with the proposed cutting area.
5. Use deflection lines (ground profiles) combined with a skyline payload analysis to predict specific points of possible disturbance. Identify the potential for full or partial suspension.
6. Take special care when yarding long logs, logs hooked in the centre, or logs hooked with two chokers.
7. Plan debris disposal from landings, landing ditches, and crane windrow ditches. Clean landing ditches regularly and avoid putting debris in gullies.
8. Avoid yarding operations on long steep slopes during periods of heavy rainfall. Plan to log steep areas during the summer months or use mobile yarding cranes that can be quickly moved to less steep areas during periods of heavy rainfall.
9. Use the yarding system that has the best chance to reduce yarding disturbance on steep sensitive terrain. Consider the available deflection, the size of logs, and the yarding road density of alternative systems. Reducing yarding disturbance will increase productivity and reduce the potential for initiating yarding-related failures.
10. Communicate plans and problems frequently so that all concerned planners, foremen, crew, and agency persons know what to do and what is expected of them.
11. Further research into gully stability during and after logging is necessary so that loggers can be advised how to minimize potential gully failure.

12. Root strength deterioration appears to be a much more important factor in open-slope and gully-failure initiation than yarding disturbance. Research is required on methods of site rehabilitation involving the planting of fast-growing trees and shrubs that will quickly re-establish a thrifty root network.

13. Continue to monitor the settings observed during this study to provide continual data on the changes that occur on settings following logging and the relationship of root deterioration to slope stability.

14. Demonstrate alternative yarding systems, such as helicopters and long-line skylines, on steep-slope areas to determine their costs of operation, factors limiting operations, and the terrain conditions suited to their use. Monitoring sites logged with minimal disturbance will help to determine if reduced yarding disturbance could reduce the long-term failure frequencies rather than just the short-term yarding initiated failures.

15. Maintain existing road networks through or above sensitive terrain, and re-establish drainage patterns following the winter storm periods.

It is possible to minimize the disturbance caused by yarding through careful planning and by choosing of the system best suited to the terrain. The machines and systems currently in use on the Queen Charlotte Islands are satisfactory for logging most areas. Minimizing yarding disturbance should also increase the productivity of yarders.

Logging steep, sensitive sites is difficult, and therefore it is extremely important that all persons involved cooperate and work together. This study demonstrates that yarding disturbance may be an important factor in initiating slope failures, however, may only contribute 0.5 failures per km^2 per year to the overall failure frequency on clearcuts of 3.6 failures per km^2 per year. If the remaining slope failures occur later in time, then alternative yarding systems, such as helicopters, may not be effective in reducing mass-wasting frequencies on logged areas.

7 LITERATURE CITED

Ballard R.M. and R.P. Willington. 1975. Slope instability in relation to timber harvesting in the Chilliwack Provincial Forest. For. Chron., April 1975.

Bishop, D.M. and M.E. Stevens. 1964. Landslides in logged areas in southwest Alaska. U.S. Dep. Agric. For. Serv., Northern For. Exp. Stn. Res. Pap., NOR-1.

Dyrness, C.T. 1967a. Soil surface conditions following skyline logging. U.S. For. Serv. Res. Note PNW-55.

_________. 1967b. Mass soil movements in the H.J. Andrews Experimental Forest. U.S. For. Serv. Res. Pap. PNW-42.

Fredriksen, R.L. 1970. Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds. U.S. For. Serv. Res. Pap. PNW-104.

Krag, R.K., E.A. Sauder, and G.V. Wellburn. 1986. A forest engineering analysis of landslides in logged areas on the Queen Charlotte Islands, British Columbia. B.C. Min. For., Land Manage. Rep. 43.

Megahan, W.F. 1972a. Logging, erosion, sedimentation - are they dirty words? J. For. 70(7): July 1972.

_________.1972b. Subsurface flow interception by a logging road in mountains of central Idaho. *In* Proc. of Nat. Symp. on Watersheds in Transition. 1972.

Megahan, W.F., N.F. Day, and T.M. Bliss. 1978. Landslide occurrence in the western and central northern rocky mountain physiographic province in Idaho. Paper presented at the 5th N. Am. For. Soils Conf.: Forest Soils and Land Use. Fort Collins, Colo. C.R. Youngberg (editor). Colo. State Univ., Fort Collins, Colo.

O'Loughlin, C.L. 1972. An investigation of the stability of the steepland forest soils in the coast mountains, southwest British Columbia. Ph.D. thesis. Univ. of B.C., Vancouver, B.C.

Rood, K.M. 1984. An aerial photograph inventory of the frequency and yield of mass wasting on the Queen Charlotte Islands, British Columbia. B.C. Min. For. Land Manage. Rep. No. 34.

Sauder, E.A., R.K. Krag and G.V. Wellburn. 1987. Logging and mass wasting in the Pacific Northwest with application to the Queen Charlotte Islands, B.C.; a literature review. B.C. Min. For. Land Manage. Rep. No. 53.

Schwab, J.W. 1983. Mass wasting: October-November, 1980 storm, Rennell Sound, Queen Charlotte Islands, British Columbia. B.C. Min. For., Res. Note No. 91.

Sidle, R.C. 1980. Impacts of forest practices on surface erosion. U.S. For. Serv. Extension Publ., PNW-195. Oreg. State Univ., Corvallis, Oreg.

_________. 1985. Shallow groundwater fluctuations in unstable hillslopes in coastal Alaska. Cited in R.C. Sidle, A.J. Pearce, and C.L. O'Loughlin. 1985. Hillslope stability and land use. American Geophysical Union. Washington, D.C.

Swanson, F.J. and C.T. Dyrness. 1975. Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology 3(7).

Swanson, F.J., G.W. Lienkaemper, and J.R. Sedell. 1976. History, physical effects and management implications of large organic debris in western Oregon streams. U.S. For. Serv. Gen. Tech. Rep. PNW-56. Portland, Oreg.

Swanston, D.N. 1969. Mass wasting in coastal Alaska. U.S. For. Serv. Res. Pap. PNW-83. Juneau, Ak.

_________. 1970. Principal soil movement processes influenced by road-building, logging and fire. Paper presented at a Sym. on Forest Land Uses and Stream Environment. J.T. Krygier and J.D. Hall (directors). Oreg. State Univ., For. Extension Dep., Corvallis, Oreg.

_________. 1971. Judging impact and damage of timber harvesting to forest soils in mountainous regions of western North America. Western Reforestation Coordinating Committee, Western Forestry and Conservation Association. Portland, Oreg.

__________. 1976. Erosion processes and control methods in North America. *In* Proceedings, XVI IUFRO World congress, Div. 1.

Swanston, D.N. and C.J. Dyrness. 1973. Stability of steep land. J. For. 71(5): May 1973, pp. 264-269.

Varnes, D.J. 1978. Slope movement types and processes. Landslides, analysis and control. Special Rep. 176. R.L. Schuster and R.J. Drizek (editors). Transportation Research Board Commission on Sociotechnical Systems, National Research Council, Washington, D.C.

Wilford, D.J. and J.W. Schwab. 1982. Soil mass movements in the Rennell Sound Area, Queen Charlotte Islands, British Columbia. *In* Can. Hydrol. Symp. '82. Nat. Res. Coun. of Can., Fredericton, N.B.