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Predicting Post-Logging Landslide Activity Using Terrain Attributes: Coast Mountains, British Columbia

by
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Research Disciplines: Ecology ~ Geology ~ Geomorphology ~ Hydrology ~ Pedology ~ Silviculture ~ Wildlife

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Cover Photo: Study slopes in Rogers Creek watershed, Southern Coast Mountains, BC.

SUMMARY

This paper identifies terrain types within the Coast Mountains of British Columbia that were subject to landslides following logging or logging road construction. The study collected field data from 2364 terrain polygons from watersheds primarily located in the southern Coast Mountains. The watersheds were divided into a wetter "Windward Zone" and a drier "Leeward Zone" on the basis of biogeoclimatic zones. Statistical tests were applied to the data set to identify relationships between terrain attributes and landslide occurrence following logging or road construction. Landslides were classified as occurring either in a clearcut or within a road-prism.

Overall, the rates of both clearcut- and road-related landslides tend to be much lower in the Coast Mountains study watersheds than have been observed in other areas on the coast. For example, 3.7% of the terrain polygons in the Windward Zone and 1.3% of the terrain polygons in the Leeward Zone experienced clearcut landslides >500 m^2 in size. By contrast, 17% of the polygons in study areas on the West Coast of Vancouver Island (Rollerson, Thomson and Millard, 1997) and 22% of the terrain polygons in a study in the Skidegate Plateau in the Queen Charlotte Islands (Rollerson, 1992,) experienced clearcut landslides >500 m^2 after logging. Mean clearcut landslide frequencies of 0.012 ls/ha (landslides per hectare) in the Coast Mountains Windward Zone, and 0.008 ls/ha in the Coast Mountains Leeward Zone, are an order of magnitude lower than the Vancouver Island and Queen Charlotte Islands studies at 0.08 ls/ha and 0.17 ls/ha respectively.

KEY WORDS

landslides, terrain, Coast Mountains.

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In common with other studies of post-logging landslides in the Vancouver Forest Region, specific terrain attributes were associated with higher landslide rates. Landslide rates increase as slope steepness increases, except for the very steepest slopes that likely are dominated by bedrock exposures. Increasing landslide rates with increasing slope angle is particularly true for roadfill landslides compared with clearcut landslides. Naturally unstable areas had much higher landslide rates than other areas. Gullies were generally identified as areas subject to high landslide rates, and larger gullies were usually less stable than smaller gullies.

The results of these tests can be used to develop classification systems suitable for identifying vulnerable sites before logging and road building occur.

1.0 INTRODUCTION

In this paper we focus on identifying landscapes vulnerable to landslides following logging and road building in the Coast Mountains. The study examines relationships between post-logging landslide incidence and terrain attributes that can be used to identify terrain likely to experience landslides if logging operations occur. Equally important to identifying terrain types that are likely to have landslides, is identifying terrain that is not likely to have landslides. This study examines terrain that has been subject to conventional road-building techniques and clearcut timber harvesting using cable systems. Landslide frequencies for roads and clearcut areas are determined.

Because of differences in climate that may affect landslide frequencies, we split the Coast Mountains into two arbitrary climatic zones: a Windward Zone (wetter) and a Leeward Zone (drier) on the basis of existing ecosystem mapping. The climate in the Leeward Zone was assumed to be transitional between coastal and interior (continental) conditions.

1.1 OBJECTIVES

The objectives of this study are:

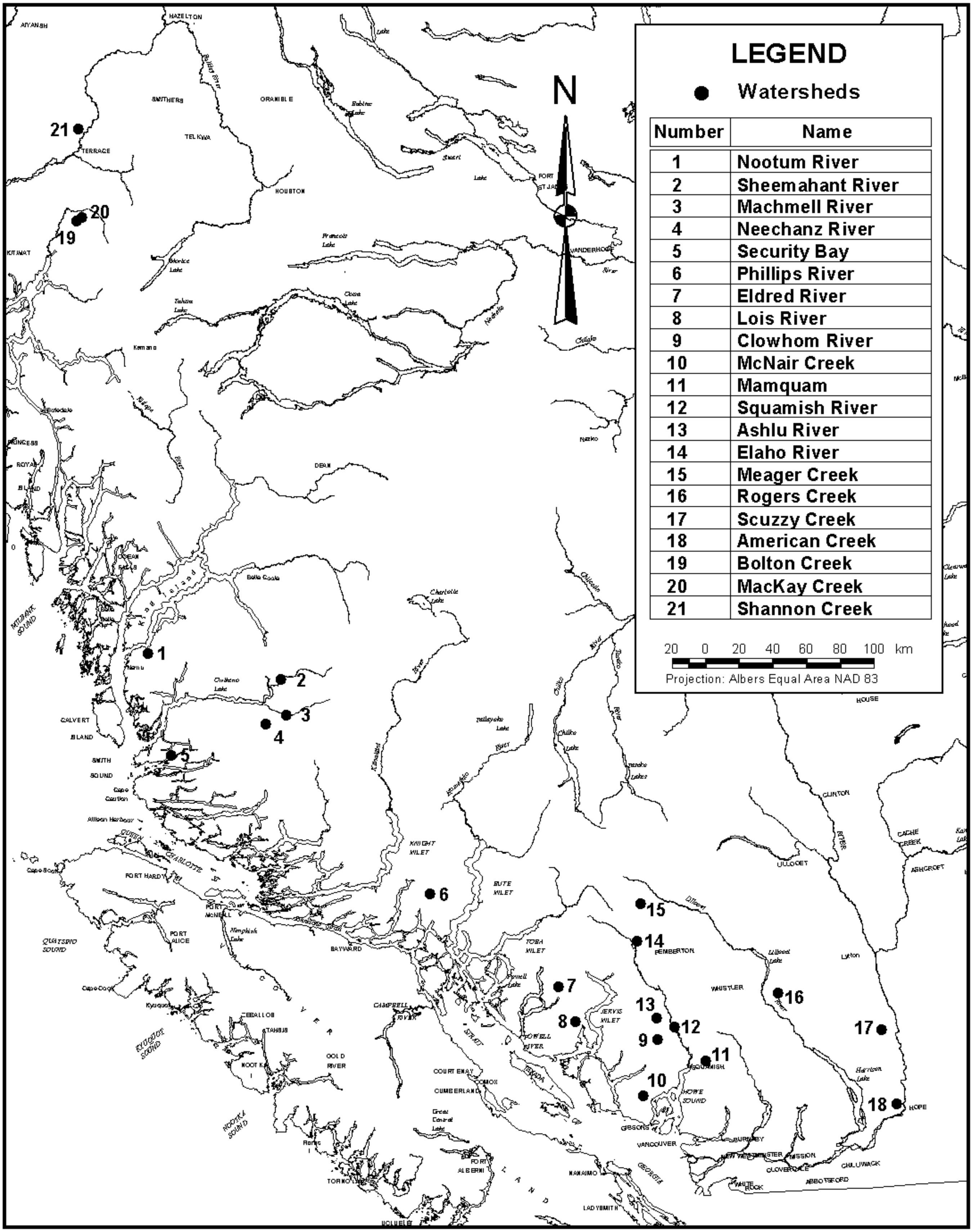
- to characterize steepland terrain types that were susceptible to landslides following forest harvesting (clearcutting) and road building in the Coast Mountains;
- to develop terrain-based stability classifications that estimate the likelihood of landslide activity following forest harvesting and road building.

2.0 STUDY AREAS

The study encompasses a number of watersheds located within the Coast Mountains of British Columbia. Most of the study watersheds occur in the southern half of the Coast Mountains (Figure 1). This region varies between a wet climate and dense forests in the west to a drier climate and more open forests in the east.

This data set is not fully representative of the Coast Mountains but it should provide a reasonable indication of relationships between post-logging landslide activity and terrain attributes that can be extended to other areas in these mountain ranges with similar geologic and climatic conditions.

Figure 1. Location map of watersheds studied



Number	Name
1	Nootum River
2	Sheemahant River
3	Machmell River
4	Neechanz River
5	Security Bay
6	Phillips River
7	Eldred River
8	Lois River
9	Clowhom River
10	McNair Creek
11	Mamquam
12	Squamish River
13	Ashlu River
14	Elaho River
15	Meager Creek
16	Rogers Creek
17	Scuzzy Creek
18	American Creek
19	Bolton Creek
20	MacKay Creek
21	Shannon Creek

2.1 PHYSICAL SETTING

2.1.1 BIOGEOCLIMATIC ZONES AND CLIMATE

The Biogeoclimatic Ecosystem Classification (BEC) is an ecological classification system used in British Columbia to group similar segments of the forest landscape into categories of a hierarchical classification system (Green and Klinka, 1994). Climate is considered to be the most important factor influencing the development and distribution of forest ecosystems in British Columbia. Because climate stations are rare in remote watersheds in the Coast Mountains we used BEC maps[1] to group or differentiate among watershed areas with respect to climate.

Three biogeoclimatic zones are found in the study areas: the Coastal Western Hemlock (CWH) zone and the Mountain Hemlock (MH) zone are dominant, but limited areas of the Interior Douglas Fir (IDF) zone are also present. The CWH zone occurs at elevations ranging from sea level to 900 m on windward slopes, and is much more prevalent in the study areas than the MH zone, which usually forms the subalpine zone above the CWH (Meidinger and Pojar, 1991). The IDF zone has limited distribution, but is found on some lower elevation slopes and valley bottoms in the central and eastern portions of the southern Coast Mountains (e.g., in the Lillooet River and the Fraser River).

The Coastal Western Hemlock zone is typically the wettest and most productive forest zone in British Columbia. The CWH zone typically experiences cool summers and mild winters. Mean annual temperatures range from 5 to 11 degrees Celsius, and mean annual precipitation ranges from 1000 to 4400 mm. Four main CWH subzones are represented within the study watersheds: the Dry Submaritime (ds), the Moist Submaritime (mm), the Very Wet Maritime (vm), and in limited areas the Very Wet Hypermaritime (vh). The Very Wet Maritime is the most extensive subzone and occurs on windward slopes throughout the Coast Mountains. The Very Wet Hypermaritime is restricted to lower elevations near the outer coast. The Submaritime subzone is restricted to the leeward side of the Coast Mountains. The Dry Submaritime is found only in the central and southern portion of the CWH zone and has a climate that is transitional between the coast and interior (Green and Klinka, 1994).

The Mountain Hemlock zone occupies elevations of 800 to 1400 m in the study areas, and experiences short, cool, moist summers and long, cold, wet winters (including heavy snow cover that can persist into July). Mean annual temperature ranges from 0 to 5 degrees Celsius. Mean annual precipitation ranges from approximately 1700 to 5000 mm, of which up to 70% is snow (Meidinger and Pojar, 1991). The two variants of the MH occurring in the study area are the Windward Moist Maritime vari-

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[1] The BEC maps for the Vancouver Forest Region used for this work were revised in 1994 by F. Nuszdorfer and R. Boettger, Vancouver Forest Region, Research Section.

Table 1. Distribution of BEC subzones by watershed[2]

Watershed	**Forest District**	**Zone[1]**	**BEC Subzones**
Nootum River	Mid Coast	W	CWHvm2/MHvh1
Sheemahant River	Mid Coast	W	CWHms2/CWHws2/MHmm2
Machmell and Neechanz Rivers	Mid Coast	W	CWHms2/CWHvm3/MHmm1 (CWHws2/MHmm2)
Security Bay	Mid Coast	W	CWHvh2/CWHvm2/MHvh1
Phillips River	Campbell River	W	CWHvm1/CWHvm2/MHmm1
Eldred River	Sunshine Coast	W	CWHvm1/CWHvm2/MHmm1
Lois River	Sunshine Coast	W	CWHdm/CWHvm2/MHmm1
Clowhom River	Sunshine Coast	W	CWHvm1/CWHvm2/MHmm1
McNair Creek	Sunshine Coast	W	CWHvm1/CWHvm2/MHmm1
Mamquam River	Squamish	W	CWHvm1/CWHvm2/MHmm1
Shannon Creek	Kalum	W	CWHws1/CWHws2
MacKay Creek	Kalum	W	CWHws1/CWHws2
Bolton Creek	Kalum	W	CWHws1/CWHws2
Squamish, Elaho, and Ashlu Rivers	Squamish	L	CWHds1/CWHms1/MHmm2
Meager Creek	Squamish	L	CWHds1/CWHms1/MHmm2
Rogers Creek	Squamish	L	CWHds1/CWHms1/MHmm2
Scuzzy Creek	Chilliwack	L	IDFww/CWHms1/MHmm2
American Creek	Chilliwack	L	CWHds1/CWHms1/MHmm2

[1] *W = Windward Zone, L = Leeward Zone*

[2] *See Green and Klinka, 1994, for complete descriptions of subzones and subzone abbreviations.*

ant (MHmm1) and the Leeward Moist Maritime variant (MHmm2). The latter has a climate transitional between the coast and the interior, so is somewhat drier and colder than the former (Green and Klinka, 1994).

The Wet Warm Interior Douglas Fir subzone (IDFww) is the only portion of the IDF that occurs within the study watersheds, and ranges in elevation from 100 to 1200 m. It has a continental climate that is transitional to a maritime climate. Summers are warm and dry. Winters are cool and relatively moist, with moderate snowfall (Green and Klinka, 1994).

The watersheds were separated on the basis of these biogeoclimatic zones into a wetter Windward Zone and a drier Leeward Zone (Table 1). Watersheds in the Windward Zone are more exposed to storms sweeping in from the Pacific, and therefore are likely to experience greater rainfall intensities.

2.1.2 PHYSIOGRAPHY

The study areas lie predominantly within the Pacific Ranges Physiographic Region, with small areas of the Security Bay and Nootum River watersheds located within the Hecate Lowlands Physiographic Region. The Pacific Ranges extend southeast from Burke Channel to the Fraser River, and contain the highest peaks in the Coast Mountains (Holland 1976). The Hecate Lowland is a strip of low-lying country along the eastern side of the Coastal Trough that extends from Prince Rupert to Vancouver. An arbitrary line along the 600 m contour was used by Holland to separate the Hecate Lowland from the Pacific Ranges to the east.

The landforms and surficial materials of the area are for the most part a legacy of repeated glaciation during the Pleistocene Epoch, which occurred between two million and 12,000 years ago. Large erosional features, such as valleys and cirques, are ubiquitous in the Pacific Ranges region. Valleys with a typical U-shaped cross-section (glacial troughs) and steep side slopes are common. Topography is rugged, with elevations ranging from sea level to almost 4000 m above sea level.

2.1.3 BEDROCK

In both the Windward Zone and the Leeward Zone, bedrock exposures are dominated by intrusive rocks. Over 80% of the bedrock exposures recorded during the study were intrusive. These intrusive rocks include quartz diorite, granodiorite, granite, diorite and quartz monzonite, but are dominated by granodiorite and quartz diorite. Metamorphic rocks are the next most common type of bedrock and account for slightly less than 17% of the recorded exposures. Metamorphic rocks included: gneiss, granitiod gness, greenstone and schist. Volcanic rocks, including limited exposures of andesitic and dacitic tuffs and occasional occurrences of basalt, are rare. Sedimentary rocks are only represented by a few exposures of graywacke. Volcanic and sedimentary rocks combined account for less than two percent of the recorded bedrock exposures.

The intrusive and harder metamorphic rocks are typically coarse grained and sparsely jointed. This latter characteristic, combined with a high resistance to weathering and erosion, allows the development of very steep, but relatively stable valley sides. The softer metamorphic and volcanic rocks tend to be fine grained. These rocks are more fractured or jointed than intrusive rocks and can be weaker and more susceptible to failure.

2.1.4 SURFICIAL MATERIALS

Typically, deposits of unconsolidated materials composed of till, colluvium, fluvial (alluvial), glaciofluvial and occasional glaciolacustrine materials are found throughout the study area. In much of the study area steep-sided rock-controlled slopes form valley walls enclosing gentle gradient flood plains. On the lower slopes and valley floors, thick deposits of till, glaciofluvial, fluvial, and to a lesser extent colluvial and glaciolacustrine materials, are found. These materials form a landscape of gentle slopes and terraces cut by steep scarps and gullies. On valley walls, bedrock outcrops with thin discontinuous coverings of till and colluvium are found in upper and midslope positions.

The intrusive rocks found in the study area break down into a predominantly coarse combination of rubble, gravel, and sandy residue, which has been incorporated into the local surficial materials. Blocky talus slopes, bouldery glacial deposits especially till, and bouldery stream gravels are characteristic of this area. Metamorphic and volcanic rocks, being finer grained, often weather to a combination of gravel, sand, and silt. Therefore till derived from these rocks tends to have a matrix that is finer than that of till associated with the intrusive rocks.

Dominant mass movement processes in the study areas include snow avalanches and/or debris flows confined to steep gullies, gully wall debris slides, rockfall from sheer valley sidewalls, and debris slides and debris flows on open bedrock-controlled slopes or on steep scarps.

3.0 METHODOLOGY

3.1 SAMPLING DESIGN

A number of watersheds were selected for study mainly within the southern Coast Mountains. Within each study watershed, all accessible logged areas, generally ranging in age from five to 15 years following harvesting, were sampled. The lower age limit was set to ensure that the study areas had experienced a number of large storms and to give time for loss in root strength to occur. The upper age limit was set because crown closure and increasing tree height in the regenerating plantations tend to mask local terrain features including small landslides, making collection of accurate data difficult. We observed a number of situations where rapidly growing conifers and alder completely masked the presence of individual landslides in clearcut areas within 10 to 15 years. As well, young alder growing on the roads made both walking and accurate observations very difficult in older areas.

Each selected area was mapped at a scale of 1:20,000 using the BC Terrain Classification System (Howes and Kenk 1997), and 1:15,000 to 1:20,000 scale aerial photography. Each terrain polygon was verified in the field. For the sake of efficiency, most terrain polygons with slopes less than 20 degrees were excluded from the study, because they rarely show evidence of post-logging failure. Each terrain polygon constituted a single sample.

The data set consists of 2,364 terrain polygons. The mean terrain polygon area is 3.6 hectares with a standard deviation of 3.7 hectares. The study areas represent about 8,490 hectares of mountainous terrain. Updating of landslide incidence may occur periodically, usually after major storm events or when new aerial photography is flown. At any point in time, the data set will likely slightly under-represent the total number of landslides that have occurred in the study areas.

With terrain mapping it is common knowledge that no two mappers will produce identical map polygons for a given landscape, or describe an area in exactly the same manner. Because this study involved several mappers, the terrain mapping approach will have introduced some unknown amount of bias or variability. This was limited by providing clear definitions and descriptions of the terrain data to be collected and by having the mappers work together with a mapping co-ordinator to ensure a consistent approach. The analysis of categorical terrain data generally involves the grouping of a large number of specific terrain types into a smaller set of more generalised terrain categories. This consolidation reduces the effect of individual differences in terrain polygon delineation and classification.

3.2 DATA COLLECTION

For each map polygon, terrain attributes such as landscape position, slope gradient, aspect, slope morphology, slope curvature, soil drainage class, surficial material, bedrock type, and the presence or absence of natural and post-logging landslides were recorded. Landslides identified in the field or on aerial photographs that were approximately 500 m^2 or larger were recorded individually. The presence of any smaller natural or post-logging landslides was tabulated as a terrain characteristic but their actual numbers were not documented because they could not be reliably identified in the field or on air photos.

3.3 DATA ANALYSIS

Two measures of landslide rate or activity were used in the analysis, landslide presence and landslide density.

Landslide presence is the presence of the initiation point of one or more clearcut landslides within a terrain polygon, or from a road within a polygon. The analysis reports the percentage of polygons with landslides present. This analysis indicates whether a polygon has experienced landslide activity or not, but does not indicate whether one landslide or several landslides were present within the polygon. Landslide presence was evaluated using three criteria:

1. Only those landslides >500 m^2 were used as the dependent variable. This criterion applies to both clearcut landslides and roadfill landslides.
2. For clearcuts, landslides of any size were used as a second dependent variable.
3. For roads, any evidence of roadfill instability was used as a second dependent variable. This measure included landslides of any size, tension cracks, fill slope settlement, or other signs of roadfill instability.

Landslide density is the total number of landslides >500 m2, divided by the polygon size. Landslide density was evaluated using two criteria:

1. For clearcut areas, landslide density was measured as landslides per hectare (ls/ha), based on slope area, not planimetric area.
2. For roadfills, the measurement was landslides per 100 m of road (ls/100 m).

This approach gave six measurement terms:

- >500 m^2 clearcut landslide presence
- >500 m^2 roadfill landslide presence
- All clearcut landslide presence
- All roadfill instability presence
- >500 m^2 clearcut landslide density
- >500 m^2 roadfill landslide density

Cross tabulation analysis and Chi-squared tests were applied to investigate relationships between landslide presence and individual terrain variables in the data set. Kruskal-Wallis tests were used to test for differences in landslide density for different terrain variables. The Kruskal-Wallis tests were supplemented with analysis of variance. We used non-parametric tests in preference to parametric tests because many geographic variables (e.g., landslide density) are often not normally distributed and/or are categorical, and because sample sizes tend to be unequal and sometimes quite small for certain categories of some variables.

Because landslide densities were generally quite low in the study area, the use of the presence of all sizes of landslides rather than just those >500 m^2 provided a more sensitive measure of post-logging landslide activity. However, it is likely that not all occurrences of landslides smaller than 500 m^2 were detected due to the difficulty of consistently identifying these smaller features both on air photos and in the field.

A limited number of the samples represent deactivated roads which have undergone significant fill slope pull back (i.e., re-contouring to eliminate the road and to re-establish the original ground slope). This work generally obliterates evidence of smaller road instability features (e.g., tension cracks). With less aggressive remedial treatments (e.g. partial fill pull back) on steep slopes, indications of instability can reappear within a few years.

In our opinion, assessment of all signs of instability associated with roadfills provides better long-term prediction of the likelihood of significant road related landslide activity. Due to the nature of much of the older logging road construction (e.g. fills supported by buried logs and stumps which are slowly rotting) more large landslides may occur as these roads age. There were a few road cut-slope landslides larger than 500 m^2 in the data set. However, because these and other indications of cut slope instability were rare, we did not carry out any analysis of stability problems associated with road cuts.

We carried out limited multivariate analyses for both landslide density and landslide presence to determine which combinations of terrain variables would most usefully predict landslide activity levels. We used a multivariate method known as CHAID (Chi-squared Automatic Interaction Detector) to group individual terrain polygons into a limited number of multi-factor terrain categories having a similar likelihood or density of post-logging failure.

CHAID uses a non-parametric, multivariate procedure known as segmentation modeling (Magidson J. /SPSS 1993). The procedure divides a sample population into two or more distinct groups based on the best predictors of a dependent variable. Segments defined by the analysis do not overlap. Dependent and predictor variables can be either categorical or continuous variables. The procedure merges categories of a predictor variable that are not significantly different at each segmentation level and splits those that are different. The analysis produces a tree diagram that identifies predictor variables and presents statistics for each separate group or segment of the dependent variable. These categories can form the basis of terrain stability classifications that estimate the likely presence or density of post-harvest landslides.

For this particular set of analyses, the probability values for splitting and merging categories within the CHAID segmentation tree were set at alpha = 0.05. We also set stopping rules of a minimum of 20 samples to split a parent node and a minimum of 10 for merging samples to form a child node. The maximum tree depth was set at four.

4.0 RESULTS

In order to simplify the analysis and presentation of the study results, we separated the data into two zones, as described earlier in this paper: a Windward Zone and a Leeward Zone. There can be significant differences in landslide frequencies between the watersheds that lie near the coast and those that are further inland. For example, the watersheds included in the Windward Zone data set had a greater percentage of terrain polygons with clearcut landslides >500 m^2, than the Leeward Zone watersheds (i.e., 3.7% versus 1.3%). The watersheds located in the Terrace area are included in the Windward Zone data set.

4.1 WINDWARD ZONE

Clearcut landslides >500 m^2 were present in 53 (3.7%) of the 1,446 terrain polygons in the Windward Zone, leaving 96.3% of the samples without landslides. The percentage of polygons with post-logging landslides increased to 9.0% when clearcut landslides smaller than 500 m^2 were considered. Roadfill landslides >500 m^2 were present in 42 or 4.3% of 983 sample terrain polygons containing roads. If all roadfill landslides and other signs of instability recorded were considered, then 166 or 16.9% of the sample of polygons with recorded road lengths exhibited some form of roadfill instability.

There were significant differences for landslide frequencies among the various sample watersheds in the Windward Zone (Tables 2a, 2b, 3, 4a, 4b and 5). These values ranged from 0.8% to 8.7% for terrain polygons with clearcut landslides >500 m^2 present, and from 2.3% to 20.7% if all the smaller clearcut landslides recorded were included. Similarly, the range among different watersheds for terrain polygons with roadfill landslides was 0.0 to 25.0% but increased to 3.7 to 61.1% when all instances of roadfill instability were considered. These differences likely resulted from local climatic differences between watersheds and differences in the distribution of surficial materials, slope morphology, slope angle and the like. Except for one watershed with steeper average slopes, a means plot did not show

Table 2a. Terrain Attributes and Post-Logging Landslide Presence, Windward Zone

Variable	Significance Level Pearson Chi-Square	
	Landslides >500 m^2	all landslides
Slope class	.291	.000
Natural landslides present	.052	.015
Landscape position	.425	.747
Slope morphology	.021	.000
Terrain category	.344	.133
Dominant surficial material	.862	.772
Horizontal curvature	.927	.000
Vertical curvature	.005	.000
Soil drainage	.477	.000
Slope aspect (by octant)	.754	.634
Elevation	.394	.763
Bedrock lithology	.783	.372
Bedrock structure	.637	.592
Bedrock hardness	.338	.012
Age of logging	.548	.565
Watershed	.032	.000

Table 2b. Terrain Attributes and Post-Logging Landslide Densities, Windward Zone

Variable	Significance Levels	
	Kruskal -Wallis	Anova
Slope class	.285	.367
Natural landslides present	.052	.369
Landscape position	.425	.550
Slope morphology	.012	.182
Terrain category	.356	.883
Dominant surficial material	.766	.836
Horizontal curvature	.967	.861
Vertical curvature	.005	.288
Soil drainage	.479	.665
Slope aspect (by octant)	.742	.503
Elevation	.414	.657
Bedrock lithology	.791	.820
Bedrock structure	.637	.883
Bedrock hardness	.347	.521
Age of logging	.554	.736
Watershed	.031	.031

Table 3. Terrain Attributes - Clearcut Landslides Summary Statistics, Windward Zone

Variable	Code	n	Slides >500 m^2 (ls/ha)	Slides >500 m^2 % units failing	All slides % units failing
Slope class (⊛)					
15-19	1	11	.000	0.0	9.1
20-26	2	314	.004	1.6	3.5
26-30	3	363	.015	4.4	8.3
31-35	4	424	.013	4.0	8.5
36-40	5	198	.017	5.6	12.6
41-46	6	87	.021	3.4	21.8
>46	7	49	.004	2.0	16.3
Natural Landslides					
absent	0	1389	.012	3.6	8.9
present	1	5	-	-	-
Landscape position					
upper slope	2	9	.00	-	-
mid slope	3	1156	.014	4.1	9.0
lower slope	4	278	.006	2.2	9.3
stream escarpment	5	3	-	-	-
Slope morphology					
uniform	1	919	.012	3.3	5.3
benchy	2	11	.062	9.1	18.2
dissected (gullied)	3	121	.021	9.1	23.1
irregular	5	230	.008	3.5	6.9
single gullies	6	165	.011	1.8	21.8
Terrain category					
Morainal (till)	1	493	.015	3.8	9.1
Colluvial	2	134	.005	0.7	2.2
Glaciofluvial	3	34	.010	2.9	11.8
Rock	5	13	.000	0	0.0
Morainal+colluvial	6	212	.016	6.1	11.8
Morainal+glaciofluvial	7	5	-	-	20.0
Morainal/rock	8	238	.016	5.0	11.3
Colluvial/rock	9	120	.002	1.7	6.7
Rock/colluvial (1)	10	190	.009	2.6	8.9
Volcanic (unconsolidated)	11	3	-	-	-
Glaciofluvial/glaciolacustrine	12	4	-	-	-
Dominant surficial material					
Colluvium	1	346	.009	3.2	7.2
Glaciofluvial	5	35	.010	2.9	11.4
Moraine (till)	8	860	.014	4.2	9.8
Bedrock	10	204	.009	2.4	8.3
Volcanic (unconsolidated)	11	1	-	-	-
Horizontal curvature					
concave	1	225	.012	3.6	15.1
convex	2	178	.017	3.4	6.7
straight	3	1038	.012	3.8	7.9
complex	4	5	-	-	-
Vertical curvature					
concave	1	66	.022	4.5	18.2
convex	2	60	.003	1.7	8.3
straight	3	1318	.012	3.6	8.4
complex	4	2	-	-	-
Soil drainage					
rapidly	1	157	.011	3.2	17.2
well	2	1255	.013	3.8	7.7
moderately well	3	34	.000	0.0	17.6
Slope aspect					
NNE	1	197	.007	2.5	8.6
ENE	2	265	.019	4.5	10.2
ESE	3	168	.017	5.4	11.9
SSS	4	174	.007	2.3	6.9
SSW	5	208	.018	4.3	9.1
WSW	6	232	.008	3.0	6.5
WNW	7	99	.004	3.0	10.1
NNW	8	103	.011	3.9	9.7
Elevation (m)					
0-100	1	98	.003	2.0	10.1
101-200	2	101	.015	2.0	7.8
201-300	3	143	.008	2.8	8.4
301-400	4	206	.008	2.4	6.8
401-500	5	228	.012	3.5	8.8
501-600	6	127	.017	3.9	9.4
601-700	7	104	.011	2.9	6.7
701-800	8	103	.018	7.8	9.7
801-900	9	94	.009	4.3	8.5
901-1000	10	127	.027	6.3	14.2
1001-1100	11	115	.008	3.5	9.6
Bedrock					
intrusive (mainly quartz diorite and granodiorite)	1	728	.012	4.3	9.6
volcanic (andesite/basalt)	2	12	.000	0.0	0.0
metamorphic (granite gneiss and gneiss)	3	190	.17	3.7	7.4
Greywacke	4	10	.000	0.0	0.0
Bedrock structure					
massive	1	26	.019	7.7	11.5
fractured	2	682	.015	4.7	8.5
sheared	3	8	-	-	-
Bedrock hardness					
very soft	1	1	-	-	-
soft	2	9	-	-	-
average	3	77	.000	0.0	0.0
hard	4	229	.010	5.2	12.7
very hard	5	572	.017	4.2	9.1

[1] *proportion symbols: / = dominant/subdominant; + = either component may be dominant or they may be equivalent.*

[2] *a dash (-) is used to indicate situations where small sample sizes preclude analysis*

dramatic differences in mean slope angle among the various sample watersheds.

4.1.1 WINDWARD ZONE CLEARCUT LANDSLIDES – UNIVARIATE ANALYSIS

The percentage of terrain polygons with clearcut landslides present and clearcut landslide density do not vary significantly with time elapsed since logging within the Windward Zone (Tables 2a and 2b). The sample set has a range of 4 to 21 years since logging. These results indicate that most post-logging landslides occur within 5 years of harvest.

The presence of post-logging clearcut landslides showed a statistically significant relationship for only a few of the variables tested (Tables 2a, 2b and 3).

Slope morphology was important for all measures of clearcut landslide activity, with gullied terrain tending to a have higher incidence of landslide activity than non-gullied terrain. Slope angle was statistically significant when all landslides were considered, but not when landslide incidence was restricted to landslides >500 m^2. Landslide incidence tended to increase as slope angle increased to the mid-40 degree range and then tended to drop off, likely because bedrock outcrops were beginning to dominate the landscape and there was less soil available to fail.

Slopes that were concave in the vertical direction tended to be more failure prone than convex or straight slopes. There was a higher incidence of smaller landslides on slopes that were concave along the horizontal, but the relationship was not significant when only landslides >500 m^2 were considered.

Similarly, soil drainage was significant when all sizes of landslides were considered, with rapidly drained and moderately well drained slopes being more prone to landslides than well-drained slopes. The most obvious explanation for this relationship is that shallow, rapidly drained soils tend to be associated with steeper slopes, and moderately well drained areas can contain local zones of imperfectly or poorly drained soils.

Elevation and aspect showed no relationship to landslide activity. The variable terrain category expresses in a general way the different combinations of surficial materials present in the landscape. Colluvial and bedrock dominated landforms appeared to be more stable, whereas landforms dominated by morainal, glaciolacustrine and some glaciofluvial materials appeared to experience higher landslide frequencies (Table 3). However, the statistical tests showed no significant differences among these different terrain categories.

4.1.2 WINDWARD ZONE ROADFILL LANDSLIDES AND INSTABILITY – UNIVARIATE ANALYSIS

The incidence of instability related to roadfills within the Windward Zone of the Coast Mountains showed similar trends to the incidence of clearcut landslides (Tables 4 and 5), with roadfill landslide activity being most closely associated with changes in slope angle and slope morphology.

There were statistically significant differences in the frequency of roadfill instability over time (Table 4a and 4b) but inspection of the data showed no obvious trend of increasing instability as the roads age. We speculate that the differences in the frequency of fill slope instability with differing ages of logging were due to local variations in terrain, road construction and other conditions specific to the location and age of roads.

Roadfill instability was significantly related to slope angle, increasing as slope angle increased. Gullied terrain had the highest incidence of road instability. Uniform slopes were intermediate between irregular or benchy slopes and gullied terrain.

Terrain category was significantly related to roadfill instability only when all types of roadfill instability were considered. In this case, terrain dominated by morainal materials was more frequently associated with evidence of roadfill instability. There was some indication that roadfills on hill slopes facing towards the northeast and southwest were less stable. Similarly, hard intrusive bedrock may be associated with a slightly higher incidence of fill slope instability than other rock types.

Landscape position, slope curvature, and soil drainage conditions appeared to have no or only limited influence on roadfill stability.

4.1.3 WINDWARD ZONE CLEARCUT LANDSLIDES – MULTIVARIATE ANALYSIS

Analysis of the Windward Zone data using CHAID was more successful when all sizes of landslides were considered than when only landslides >500 m^2 were considered.

For clearcut landslides >500 m^2, CHAID found only slope angle to be a useful predictor of landslide density. Slope angles greater and less than 35° were associated with mean landslide densities of 0.008 and 0.024 ls/ha respectively, not a particularly useful separation. In the case of the presence or absence of clearcut landslides >500 m^2 CHAID did not detect any significant predictor variables.

When the presence of all sizes of clearcut landslides was considered, then CHAID was able to identify several significant predictor variables (Figure 2). In this case, slope morphology, maximum slope angle, gully depth, dominant surficial material, and soil drainage class were used to define a series of dichotomous splits in the data. Gullies deeper than about four meters, and benchy areas and gullies with either rapidly drained or moderately well drained soils, were associated with the highest percentage of terrain units experiencing post-logging clearcut landslide activity.

Table 4a. Terrain Attributes and Roadfill Landslides or Instability Presence, Windward Zone

Variable	Significance Level Pearson Chi-Square	
	landslides >500 m^2	roadfill instability
Slope class	.000	.000
Natural landslides present	.714	.021
Landscape position	.816	.465
Slope morphology	.012	.079
Terrain category	.203	.001
Dominant surficial material	.940	.262
Horizontal curvature	.460	.142
Vertical curvature	.932	.009
Soil drainage	.996	.410
Slope aspect (by octant)	.441	.003
Elevation	.728	.239
Bedrock lithology	.208	.020
Bedrock structure	.171	.296
Bedrock hardness	.038	.029
Age of logging (road building)	.019	.001
Watershed	.007	.000

Table 4b. Terrain Attributes and Roadfill Landslide Densities, Windward Zone

Variable	Significance Levels	
	Kruskal-Wallis	Anova
Slope class	.000	.001
Natural landslides present	.714	.816
Landscape position	.808	.152
Slope morphology	.013	.455
Terrain category	.185	.103
Dominant surficial material	.936	.823
Horizontal curvature	.445	.098
Vertical curvature	.927	.887
Soil drainage	.996	.903
Slope aspect (by octant)	.431	.116
Elevation	.733	.881
Bedrock lithology	.213	.614
Bedrock structure	.171	.686
Bedrock hardness	.040	.153
Age of logging	.013	.004
Watershed	.009	.229

Table 5. Terrain Attributes - Roadfill Landslides and Stability Summary Statistics, Windward Zone

Variable	Code	n	Slides >500 m^2 (ls/100m of road)	Slides >500 m^2 % units failing	% units with roadfill instability
Slope class (°)					
15-19	1	5	-	-	-
20-26	2	226	.001	0.4	4.9
26-30	3	250	.013	2.0	17.2
31-35	4	296	.059	4.4	19.3
36-40	5	124	.156	12.1	28.2
41-46	6	55	.049	7.3	27.3
>46	7	27	.243	14.8	18.5
Natural Landslides					
absent	0	980	.051	4.3	16.7
present	1	3	-	-	-
Landscape position					
upper slope	2	3	-	-	-
mid slope	3	796	.038	4.0	17.7
lower slope	4	183	.108	5.5	13.7
stream escarpment	5	1	-	-	-
Slope morphology					
uniform	1	637	.058	4.4	16.8
benchy	2	8	-	-	-
dissected (gullied)	3	80	.088	10	25.0
irregular	5	134	.000	0	10.4
single gullies	6	124	.045	4.8	19.4
Terrain category					
Morainal (till)	1	348	.078	4.9	16.4
Colluvial	2	99	.011	2.0	6.1
Glaciofluvial	3	27	.043	3.7	11.1
Rock	5	6	-	-	-
Morainal+colluvial	6	153	.034	5.9	26.1
Morainal+glaciofluvial	7	3	-	-	-
Morainal/rock	8	160	.027	1.3	15.6
Colluvial/rock	9	73	.042	5.5	11.0
Rock/colluvial (1)	10	110	.049	5.5	22.7
Volcanic (unconsolidated)	11	1	-	-	-
Glaciofluvial/ glaciolacustrine	12	3	-	-	-
Dominant surficial material					
Colluvium	1	235	.026	3.4	13.6
Glaciofluvial	5	28	.042	3.6	10.7
Moraine (till)	8	602	.062	4.5	17.4
Bedrock	10	117	.046	5.1	22.2
Volcanic (unconsolidated)	11	1	-	-	-
Horizontal curvature					
concave	1	151	.119	6.6	23.2
convex	2	121	.018	3.3	16.5
straight	3	709	.042	3.9	15.7
complex	4	2	-	-	-

Variable	Code	n	Slides >500 m^2 (ls/100m of road)	Slides >500 m^2 % units failing	% units with roadfill instability
Vertical curvature					
concave	1	43	.035	4.7	18.6
convex	2	42	.009	2.4	35.7
straight	3	897	.053	4.3	15.9
complex	4	1	-	-	-
Soil drainage					
rapidly	1	90	.034	44	14.4
well	2	869	.052	4.3	17.4
moderately well	3	24	.049	4.2	8.3
Slope aspect					
NNE	1	145	.049	5.5	15.9
ENE	2	176	.078	6.3	25.0
ESE	3	104	.039	2.9	17.3
SSS	4	128	.021	3.1	10.9
SSW	5	145	.032	4.8	21.4
WSW	6	154	.035	3.2	16.9
WNW	7	68	.179	5.9	5.9
NNW	8	63	.000	0.0	9.5
Elevation (m)					
0-100	1	70	.071	5.7	8.6
101-200	2	62	.054	1.6	6.5
201-300	3	101	.083	2.0	14.9
301-400	4	133	.019	3.8	18.0
401-500	5	150	.032	3.3	19.3
501-600	6	76	.027	3.9	19.7
601-700	7	80	.033	5.0	17.5
701-800	8	73	.081	6.8	15.1
801-900	9	66	.017	3.0	18.2
901-1000	10	91	.098	5.5	18.7
1001-1100	11	81	.062	7.4	23.5
Bedrock					
intrusive (mainly quartz diorite and granodiorite)	1	485	.045	4.5	19.8
volcanic (andesite/basalt)	2	10	.000	0.0	0.0
metamorphic (granite gneiss and gneiss)	3	122	.011	.8	10.7
Greywacke	4	9	.000	0.0	0.0
Bedrock structure					
massive	1	18	.000	0.0	5.6
fractured	2	472	.049	4.7	20.6
sheared	3	5	-	-	-
Bedrock hardness					
soft	2	4	-	-	-
average	3	50	.013	2.0	4.0
hard	4	166	.091	8.4	22.9
very hard	5	379	.031	3.2	19.3

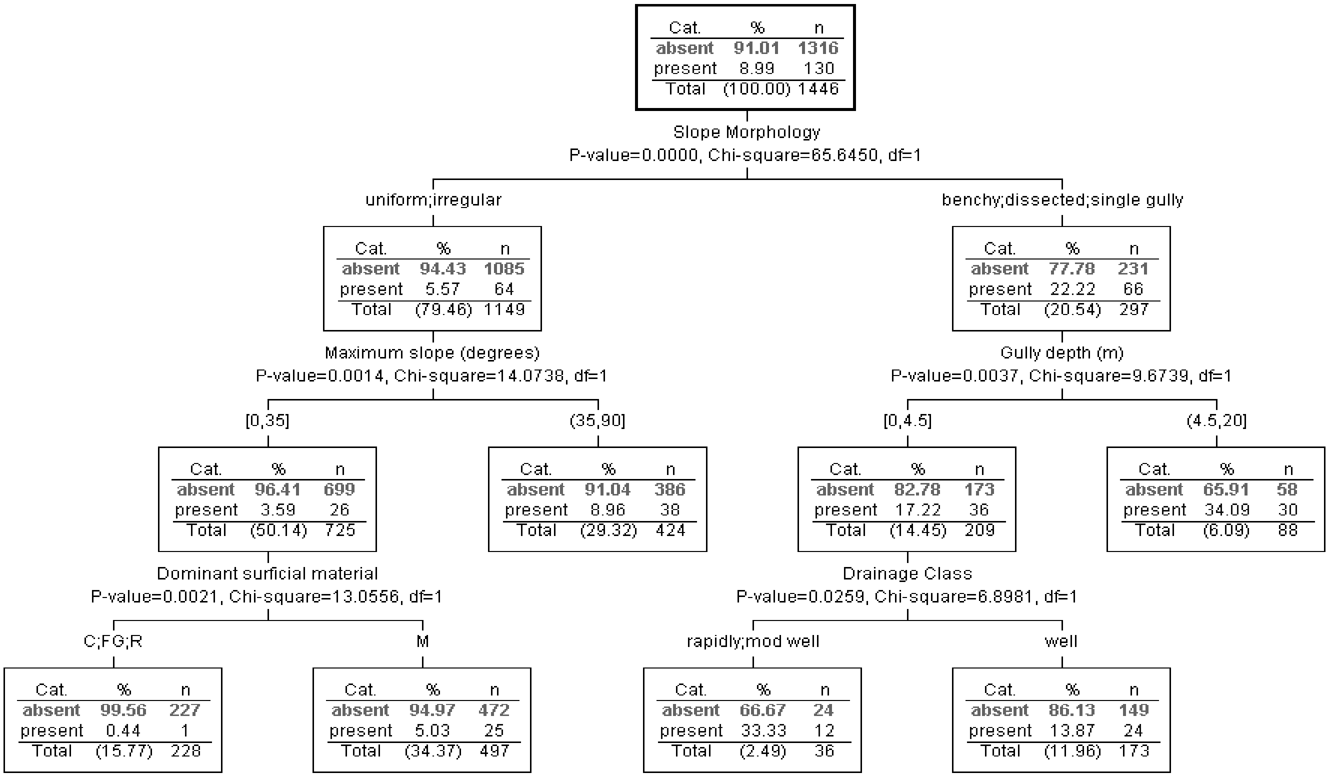
[1] *proportion symbols: / = dominant/subdominant; + = either component may be dominant or they may be equivalent.*

4.1.4 WINDWARD ZONE ROADFILL LANDSLIDES AND INSTABILITY – MULTIVARIATE ANALYSIS

In the case of roadfill landslide densities for landslides >500 m^2, CHAID used two predictor variables – the minimum slope angle recorded for each terrain polygon, and terrain category – to split the data (Figure 3). Roadfill landslide densities were separated into three groups on the basis of increasing minimum slope angle. The steepest slope category, those areas where the minimum slope angle was >34°, were separated into two groups, one dominated by morainal, glaciofluvial and glaciolacustrine materials and the other dominated by colluvial materials and bedrock or morainal materials associated with either colluvium or bedrock. These two groups had mean landslide frequencies of 0.945 and 0.077 ls/100 meters of road respectively. If the alpha for category separation was set at 0.1 rather than 0.05, a further split of the colluvial and bedrock dominated category was made on the basis of bedrock type, or in this case, the presence or absence of bedrock[3] in the terrain unit (Figure 4).

CHAID produced a similar set of segmentations for the presence of landslides >500 m^2, using minimum slope angle, and

Figure 2. CHAID tree for all clearcut landslide presence– Windward Coast Mountains



slope morphology with a final separation of terrain units with and without bedrock exposed in the terrain unit or in the road cut (Figure 5).

When all instances of roadfill instability were considered (e.g., roadfill landslides of all sizes, tension cracks and settlement of the roadfill), CHAID was able to separate a greater number of categories. In this case CHAID used, in sequence, minimum slope angle, terrain category, the presence of gullies deeper than three meters, landscape position, and bedrock type to separate differing categories of fill slope instability (Figure 6). In this particular case, we also included as a variable road length within the terrain polygons, and found it was an effective predictor for one split.

4.2 LEEWARD ZONE

Only 12 (1.3%) of the 918 samples in the Leeward Zone had clearcut landslides >500 m^2, leaving 906 or 98.7% of the samples without landslides. The percentage of polygons with landslides increased to 5.6 % if all observations of clearcut landslides smaller than 500 m^2 were included. A total of 20 or 2.9% of the 692 terrain units with road lengths recorded had roadfill landslides that were >500 m^2. When all signs of roadfill instability were included, then 216 or 31.2% of the polygons with roads exhibited some form of fill slope instability.

There were significant differences in the frequencies of both clearcut and roadfill landslides >500 m^2 among the various sample watersheds in the Leeward Zone (Tables 6a, 6b, 7, 8a, 8b and 9). When landslides of all sizes were considered, clearcut landslide incidence did not vary significantly among these watersheds, but the incidence of fill slope instability did. The values ranged from 0.3% to 5.9% for polygons with clearcut landslides >500 m^2 present, and from 5.2% to 7.7% when the presence of smaller clearcut landslides was evaluated. The range among different Leeward Zone watersheds for sample polygons containing larger roadfill landslides varied from 0.0 to 7.7% of all terrain polygons. The incidence of road instability increased from 16.3 to 72.7% of the terrain polygons with roads when all indications of roadfill instability were included.

The percentage of terrain polygons experiencing clearcut landslides following logging did not vary significantly with the age of logging within the Leeward Zone (Table 6). The sample set had an age range of three to 20 years, but only six of the samples represented clearcut areas less than five years old. It appeared that the initiation of new clearcut failures decreased substantively within a few years of logging. There were statistically significant differences in the frequency of roadfill instability over time (Table 8a and 8b). However, as in the Windward Zone, the data showed no clear trend of increasing instability as the roads aged.

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[3] When interpreting the CHAID segmentation trees, be aware that the term 'missing' listed with some bedrock variables (i.e., bedrock type and bedrock structure) indicates that deeper surficial materials are likely present. That is, bedrock was not exposed in the cut slopes of roads traversing these polygons.

Figure 3. CHAID tree for >500 m^2 roadfill landslide densities (ls/100 meters) – Windward Coast Mountains

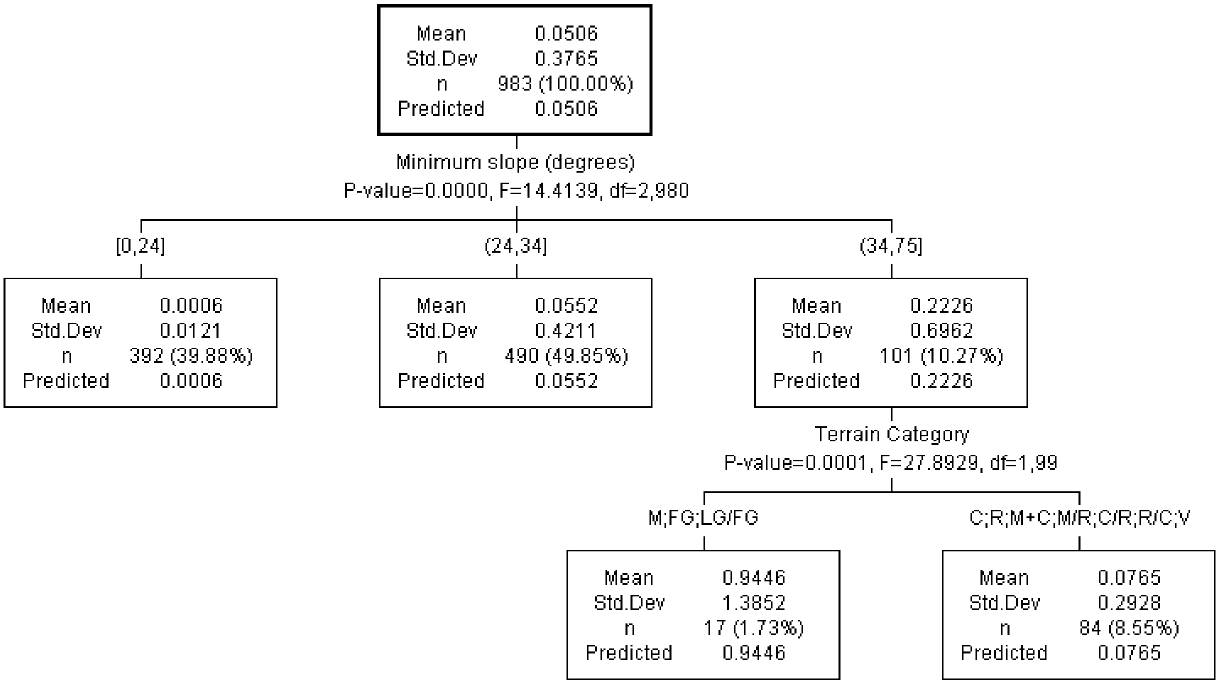


Figure 4. CHAID tree for >500 m^2 roadfill landslide densities (ls/100 meters) – Windward Coast Mountains

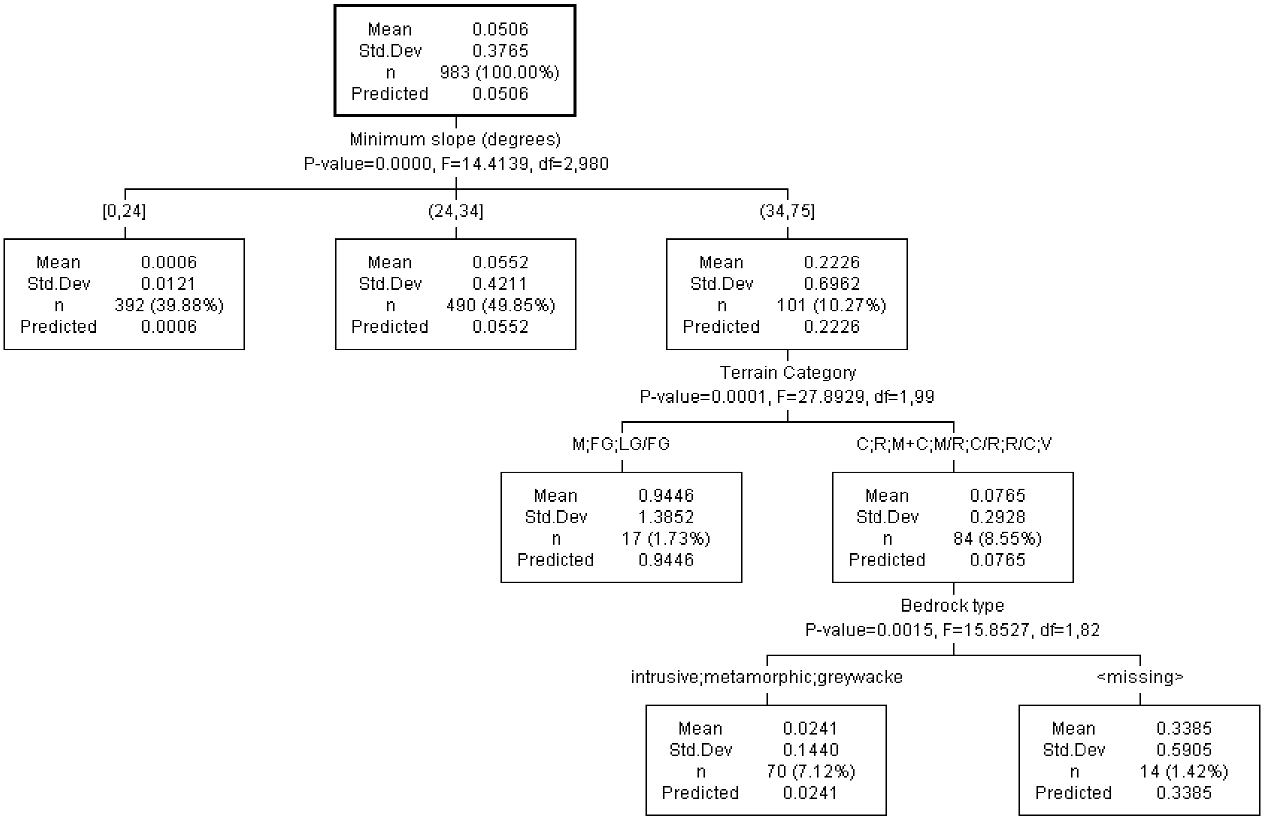


Figure 5. CHAID tree for >500 m² roadfill landslide presence – Windward Coast Mountains

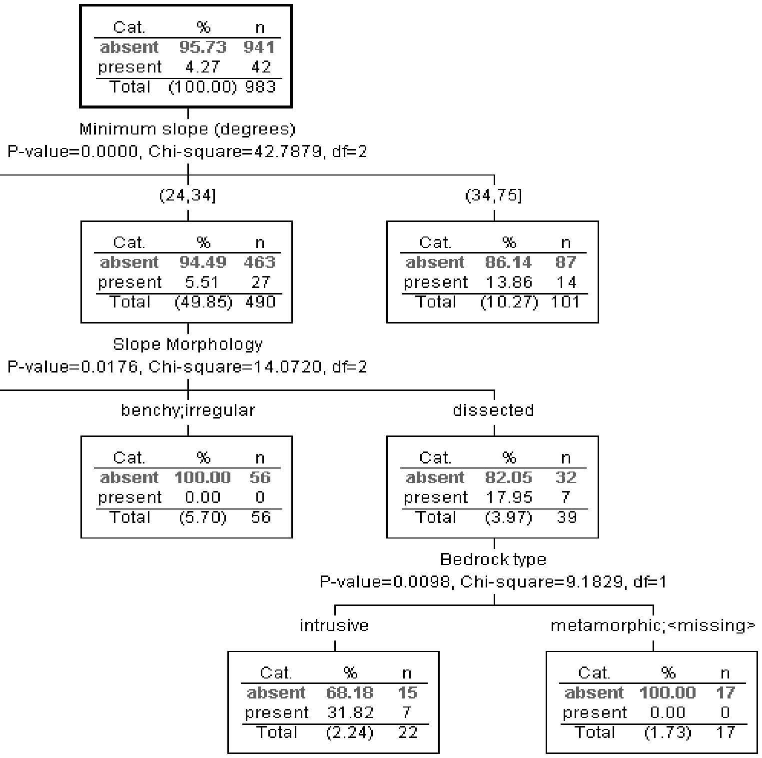
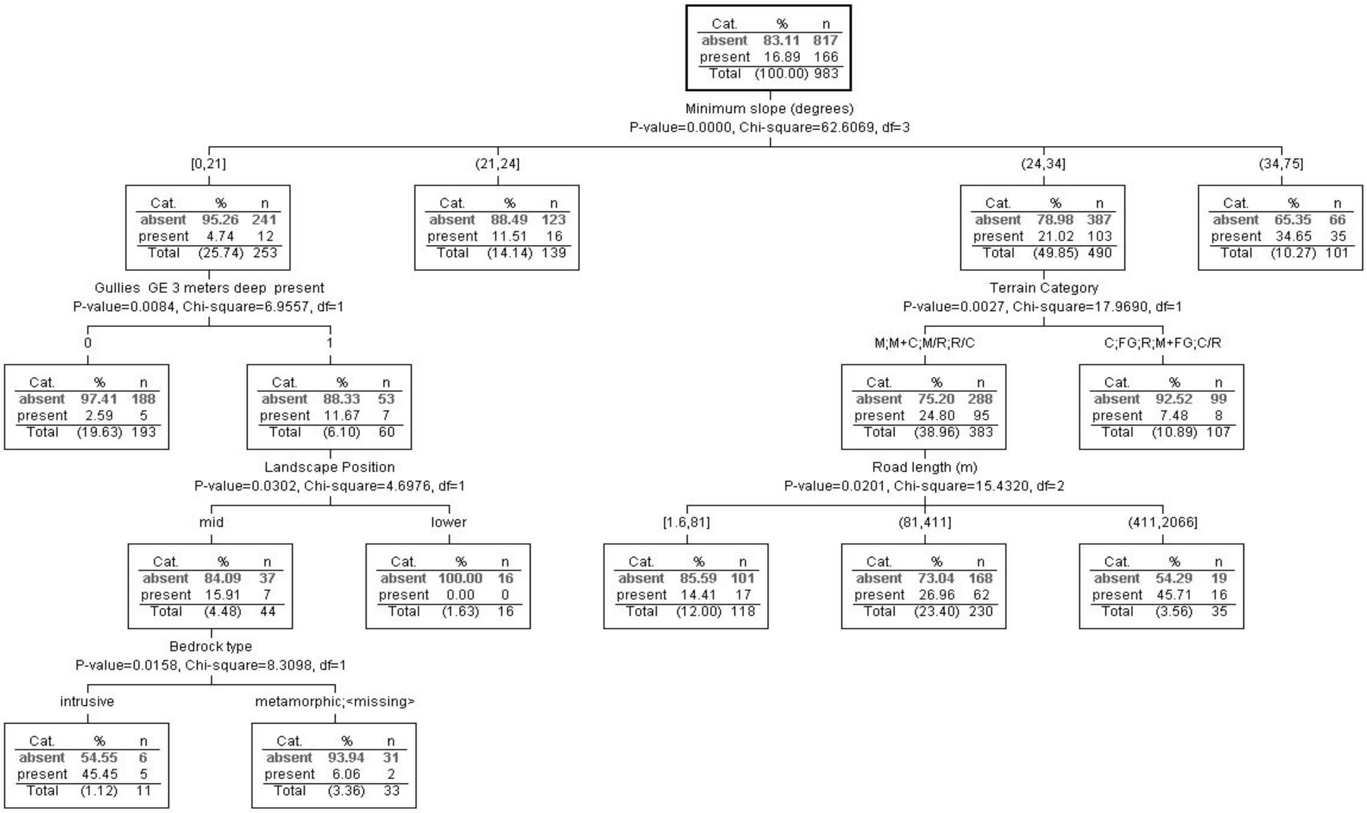


Figure 6. CHAID tree for all roadfill instability presence – Windward Coast Mountains



4.2.1 LEEWARD ZONE CLEARCUT LANDSLIDES – UNIVARIATE ANALYSIS

The incidence of larger post-logging clearcut landslides showed a statistically significant relationship for only a limited number of the variables, but a greater number of the variables were significant when the smaller landslides were included in the analysis (Tables 6a, 6b and 7).

All measures of clearcut landslide activity varied significantly with slope angle. Landslides were absent on the small population of slopes > 46° which tends to represent terrain units dominated by bedrock outcrops. Slope morphology was important when all clearcut landslides were considered, but not for the group of clearcut landslides >500 m^2. When all landslides were considered, gullied terrain had a higher incidence of landslide activity than non-gullied terrain.

The variables terrain category and dominant surficial material were both significantly related to landslide incidence. Glaciofluvial materials and complexes of glaciofluvial and morainal or glaciolacustrine materials tended to be most prone to failure. These relationships were clearer when all landslides were considered. The sample set for glaciolacustrine terrain was very limited so it was not considered in this analysis.

Slope curvature was not a significant predictor of landslides >500 m^2, but was significant when all landslides were considered, in which case curvature along the horizontal was significant. The highest incidence of post-logging clearcut landslides occurred on slopes that exhibited concave or complex curvature (i.e., both concave and convex slopes) along the horizontal contour. Unlike the Windward Zone, soil drainage was not significantly related to clearcut landslide incidence. Elevation and aspect showed no relationship to clearcut landslide activity.

Bedrock type, structure, and hardness were all significantly linked to landslide activity in the Leeward Zone. The limited sample of terrain underlain by metamorphic rocks exhibited a higher than average incidence of post-logging clearcut landslide activity when all landslides were considered, compared with areas underlain by intrusive bedrock.

4.2.2 LEEWARD ZONE ROADFILL INSTABILITY – UNIVARIATE ANALYSIS

Roadfill landslides and instability within the Leeward Zone of the Coast Mountains show similar trends to those found in the Windward Zone (Tables 8a, 8b and 9). Roadfill stability was strongly related to slope angle, with the frequency of landslides and evidence of instability increasing as slope angle increased. There was a moderately strong relationship with slope morphology. Gullied terrain typically exhibited the highest frequency of fill slope landslides and other evidence of instability.

There was no significant relationship between terrain category or surficial materials and fill slope instability. There was no apparent relationship between landscape position, slope curvature or soil drainage regime and fillslope landslides or fillslope instability.

There was no significant relationship between slope aspect and landslide activity for roadfill landslides >500 m^2, but when all evidence of roadfill instability was considered, slope aspect was significant. A higher percentage of terrain units experienced fill slope instability on slopes which face northeast and southeast to southwest than on slopes with other orientations.

There were no significant differences for different elevation bands when roadfill landslides >500 m^2 were considered. How-

Table 6a. Terrain Attributes and Post-Logging Landslide Presence, Leeward Zone

Variable	Significance Level Pearson Chi-Square landslides >500 m^2	 all landslides
Slope class	.001	.000
Natural landslides present	.000	.000
Landscape position	.275	.010
Slope morphology	.482	.000
Terrain category	.061	.000
Dominant surficial material	.007	.000
Horizontal curvature	.164	.000
Vertical curvature	.758	.122
Soil drainage	.403	.968
Slope aspect (by octant)	.539	.403
Elevation	.232	.100
Bedrock	.000	.000
Bedrock structure	.000	.000
Bedrock hardness	.000	.000
Age of logging	.768	.818
Watershed	.013	.633

Table 6b. Terrain Attributes and Post-Logging Landslide Densities, Leeward Zone

Variable	Significance Levels Kruskal-Wallis	 Anova
Slope class	.001	.270
Natural landslides present	.000	.000
Landscape position	.274	.607
Slope morphology	.350	.501
Terrain category	.059	.133
Dominant surficial material	.046	.226
Horizontal curvature	.165	.590
Vertical curvature	.757	.848
Soil drainage	.402	.545
Slope aspect (by octant)	.532	.010
Elevation	.230	.640
Bedrock lithology	.000	.000
Bedrock structure	.000	.000
Bedrock hardness	.000	.150
Age of logging	.766	.689
Watershed	.013	.005

Table 7. Terrain Attributes - Clearcut Landslides Summary Statistics, Leeward Zone

Variable	Code	n	Slides >500 m^2 (ls/ha)	Slides >500 m^2 % units failing	All slides % units failing
Slope class (°)					
15-19	1	4	.029	-	-
20-26	2	186	.000	0.0	0.0
26-30	3	245	.000	0.8	2.0
31-35	4	277	.017	1.8	6.5
36-40	5	173	.009	1.7	12.7
41-46	6	21	.035	4.8	23.8
>46	7	12	.000	0.0	0.0
Natural Landslides					
absent	0	905	.006	0.9	4.5
present	1	13	.158	30.8	76.9
Landscape position					
upper slope	2	30	.017	3.3	3.3
mid slope	3	765	.006	1.0	4.7
lower slope	4	123	.014	2.4	11.4
stream escarpment	5	0	-	-	-
Slope morphology					
uniform	1	595	.012	1.9	3
benchy	2	15	.000	0.0	6.7
dissected (gullied)	3	94	.001	1.1	9.6
irregular	5	112	.000	0.0	2.7
single gullies	6	102	.000	0.0	15.7
Terrain category					
Morainal (till)	1	305	.010	1.3	3.3
Colluvial	2	84	.000	0.0	0.0
Glaciofluvial	3	61	.016	3.3	14.8
Glaciolacustrine	4	7	-	-	-
Rock	5	17	.000	0.0	0.0
Morainal+colluvial	6	122	.007	2.5	6.6
Morainal+glaciofluvial	7	15	.000	0.0	26.7
Morainal/rock	8	100	.005	1.0	5.0
Colluvial/rock	9	45	.000	0.0	4.4
Rock/colluvial (1)	10	112	.000	0.0	0.9
Volcanic (unconsolidated)	11	30	.000	0.0	10.0
Glaciofluvial/ Glaciolacustrine	12	20	.084	10.0	40.0
Dominant surficial material					
Colluvium	1	181	.003	0.6	2.8
Glaciofluvial	5	70	.014	2.9	15.7
Glaciolacustrine	7	9	.083	-	-
Moraine (till)	8	492	.010	1.6	5.5
Bedrock	10	131	.000	0.0	1.5
Volcanic (unconsolidated)	11	29	.000	0.0	10.3
Undifferentiated	14	6	-	-	-
Horizontal curvature					
concave	1	184	.014	2.7	12.5
convex	2	155	.000	0.0	0.6
straight	3	564	.008	1.2	4.4
complex	4	15	.000	0.0	13.3

Variable	Code	n	Slides >500 m^2 (ls/ha)	Slides >500 m^2 % units failing	All slides % units failing
Vertical curvature					
concave	1	54	.014	1.9	11.1
convex	2	74	.000	0.0	1.4
straight	3	788	.008	1.4	5.6
complex	4	2	-	-	-
Soil drainage					
rapidly	1	103	.000	0.0	5.8
well	2	773	.008	1.4	5.6
moderately well	3	42	.018	2.4	4.8
Slope aspect					
NNE	1	37	.000	0.0	2.7
ENE	2	45	.064	4.4	13.3
ESE	3	112	.001	0.9	4.5
SSS	4	168	.010	1.8	4.2
SSW	5	166	.002	0.6	4.8
WSW	6	235	.006	1.7	6.4
WNW	7	113	.008	0.9	6.2
NNW	8	42	.000	0.0	4.8
Elevation (m)					
0-100	1	5	.000	0.0	0.0
101-200	2	2	.000	0.0	0.0
201-300	3	18	.000	0.0	0.0
301-400	4	35	.000	0.0	0.0
401-500	5	42	.000	0.0	0.0
501-600	6	46	.000	0.0	10.9
601-700	7	88	.027	4.5	11.4
701-800	8	113	.000	0.0	6.2
801-900	9	85	.000	0.0	2.4
901-1000	10	113	.001	0.9	6.2
1001-1100	11	371	.013	1.9	5.4
Bedrock					
intrusive (mainly quartz diorite and granodiorite)	1	413	.002	0.5	2.9
volcanic (andesite/basalt)	2	2	-	-	-
metamorphic (granite gneiss and gneiss)	3	42	.001	2.4	16.7
Bedrock structure					
massive	1	20	.000	0.0	0.0
fractured	2	391	.002	0.5	3.6
sheared	3	1	-	-	-
platy	7	14	.002	7.1	35.7
Bedrock hardness					
average	3	5	-	-	-
hard	4	44	.011	6.8	15.9
very hard	5	371	.001	0.3	3.0

[1] *proportion symbols: / = dominant/subdominant;* **+ =** *either component may be dominant or they may be equivalent.*

ever, there were significant differences when all fill slope instability was considered. There was a general increase in presence of roadfill instability with elevation in the Leeward Zone. Slope angle, which was also linked to fill slope instability, does not increase with elevation in this area. We speculate that the relationship between elevation and fill slope instability may be linked to greater snow accumulation at higher elevations and subsequent higher water contents in roadfills during snow melt or rain-on-snow events.

There were no significant differences between roadfill landslides >500 m^2 and bedrock lithology, or hardness, but there may be with bedrock structure. When all evidence for fill slope instability was considered, then there were significant differences among bedrock lithology and structure. Metamorphic bedrock and platy structure were associated with a higher incidence of fill slope instability.

4.2.3 LEEWARD ZONE CLEARCUT LANDSLIDES – MULTIVARIATE ANALYSIS

Multivariate analysis of the Coast Mountain Leeward Zone data

Table 8a. Terrain Attributes and Roadfill Landslides or Instability Presence, Leeward Zone

Variable	Significance Level Pearson Chi-Square	
	landslides >500 m^2	roadfill instability
Slope class	.005	.001
Natural landslides	.070	.0021
Landscape position	.434	.011
Slope morphology	.000	.046
Terrain category	.683	.074
Dominant surficial material	.760	.178
Horizontal curvature	.111	.624
Vertical curvature	.931	.053
Soil drainage	.208	.139
Slope aspect (by octant)	.095	.000
Elevation	.048	.000
Bedrock	.410	.007
Bedrock structure	.007	.000
Bedrock hardness	.153	.056
Age of logging (road building)	.000	.004
Watershed	.000	.000

Table 8b. Terrain Attributes and Roadfill Landslide Densities, Leeward Zone

Variable	Significance Levels	
	Kruskal-Wallis	Anova
Slope class	.005	.002
Natural landslides	.067	.044
Landscape position	.440	.706
Slope morphology	.000	.000
Terrain category	.674	.052
Dominant surficial material	.758	.553
Horizontal curvature	.104	.008
Vertical curvature	.926	.768
Soil drainage	.201	.287
Slope aspect (by octant)	.092	.094
Elevation	.048	.413
Bedrock	.424	.619
Bedrock structure	.008	.078
Bedrock hardness	.178	.597
Age of logging (road building)	.000	.002
Watershed	.000	.001

using CHAID produces a number of useful subdivisions and groupings of the data. However, CHAID was more successful in splitting the sample population when all clearcut landslides, rather than just clearcut landslides >500 m^2, were considered.

CHAID distinguished only two groups when landslide density for clearcut landslides >500 m^2 was considered. Polygons that had natural landslides of all sizes present had a mean of 0.206 ls/ha, whereas polygons without natural landslides had a mean of 0.007 ls/ha. Similarly, CHAID used the presence or absence of natural landslides to separate terrain polygons into groups with higher and lower clearcut landslides >500 m^2 presence. In this case, polygons without natural landslides had a landslide activity rate of 0.9%, and polygons with natural landslides had a 30.8 % landslide activity rate. Neither of these analyses were particularly successful in separating terrain vulnerable to landslides from terrain not vulnerable to landslides; however, they clearly showed that areas with existing natural landslides can be expected to have higher post-logging landslide frequencies than other areas.

When clearcut landslides of all sizes were considered, CHAID first grouped the data based on the presence or absence of natural landslides of all sizes (Figure 7). It then further subdivided the group with no visible natural landslides on the basis of maximum polygon slope angle. Further divisions used terrain category or the presence or absence of gullies greater than three meters deep. Although the separations on the basis of terrain category were not entirely consistent, it appears that polygons dominated by glaciofluvial and glaciolacustrine materials were more vulnerable to post-logging landslides. Terrain units dominated by morainal materials had intermediate landslide frequencies, and colluvial and bedrock dominated units the lowest landslide frequencies (Figure 7). Terrain polygons in the steepest and gentlest slope categories exhibited the lowest likelihood of post-logging landslides. Terrain units with gullies greater than three meters deep tended to have higher landslide frequencies than terrain units with no gullies or with gullies less than three meters deep.

This particular CHAID analysis seemed to be reasonably successful in separating terrain polygons with a high or moderate likelihood of post-logging landslides from those with a negligible or low likelihood of post-logging landslides. As we note in the summary discussion, it is wise to expect differences in polygon size to bias the landslide likelihood estimates to some degree. However, we did include polygon area in this particular analysis and it was not selected as a predictor variable.

4.2.4 LEEWARD ZONE ROADFILL LANDSLIDES – MULTIVARIATE ANALYSIS

CHAID grouped >500 m^2 roadfill landslide densities based on gully depth (where ‘0’ indicates an absence of gullies of any depth), and then average polygon slope angle if gullies were absent or less than four meters deep (Figure 8). The highest road landslide densities occurred in terrain units with gullies deeper than 12 meters. In areas with no gullies or where the gullies were less than four meters deep, the higher roadfill landslide densities occurred on slopes steeper than 36°. Landslide frequencies in gullies of moderate depth (i.e., 4 to 12 meters deep) were intermediate. CHAID did not select road length as a predictor variable. CHAID was able to separate more distinct groups for roadfill landslides >500 m^2 than it did for clearcut landslides >500 m^2, and it produced a slightly larger number of distinct groups when the presence of any indication of roadfill

Table 9. Terrain Attributes - Roadfill Landslides and Stability Summary Statistics, Leeward Zone

Variable	Code	n	Slides >500 m^2 (ls/100mof road)	Slides >500 m^2 % units failing	% units with roadfill instability
Slope class (°)					
15-19	1	4	.000	-	-
20-26	2	136	.000	0.0	19.1
26-30	3	197	.002	1.5	29.9
31-35	4	210	.025	2.9	34.8
36-40	5	129	.080	7.8	41.9
41-46	6	10	.121	10.0	40.0
>46	7	6	-	-	-
Natural Landslides					
absent	0	685	.023	2.8	30.8
present	1	7	.160	14.3	71.4
Landscape position					
apex	1	0	-	-	-
upper slope	2	13	.000	0.0	53.8
mid slope	3	588	.027	3.2	32.5
lower slope	4	91	.025	1.1	19.8
Slope morphology					
uniform	1	437	.010	1.6	27.7
benchy	2	10	.000	0.0	40.0
dissected (gullied)	3	79	.048	8.9	44.3
irregular	5	84	.000	0.0	33.3
single gullies	6	82	.109	7.3	34.1
Terrain category					
Morainal (till)	1	240	.010	2.1	31.7
Colluvial	2	63	.018	1.6	27.0
Glaciofluvial	3	43	.035	7.0	46.5
Glaciolacustrine	4	4	-	-	-
Rock	5	12	.000	0.0	16.7
Morainal+colluvial	6	103	.015	1.9	30.1
Morainal+glaciofluvial	7	13	.000	0.0	69.2
Morainal/rock	8	80	.056	5.0	30.0
Colluvial/rock	9	29	.015	3.4	27.6
Rock/colluvial (1)	10	76	.042	3.9	23.7
Volcanic (unconsolidated)	11	18	.000	0.0	27.8
Glaciofluvial/ glaciolacustrine	12	11	.222	9.1	36.4
Dominant surficial material					
Colluvium	1	132	.015	2.3	28.8
Glaciofluvial	5	52	.029	5.8	40.4
Glaciolacustrine	7	5	-	-	60.0
Moraine (till)	8	391	.021	2.6	32.5
Bedrock	10	91	.062	4.4	22.0
Volcanic (unconsolidated)	11	17	.000	0.0	29.4
Undifferentiated	14	4	-	-	-
Horizontal curvature					
concave	1	134	.073	6.0	35.8
convex	2	123	.013	1.6	30.9
straight	3	423	.014	2.4	29.8
complex	4	12	.000	0.0	33.3
Vertical curvature					
concave	1	36	.034	2.8	44.4
convex	2	61	.002	1.6	19.7
straight	3	593	.027	3.0	31.7
complex	4	2	.000	-	-
Soil drainage					
rapidly	1	68	.054	5.9	23.5
well	2	594	.023	2.7	31.5
moderately well	3	30	.000	0.0	43.3
Slope aspect					
NNE	1	23	.084	8.7	56.6
ENE	2	27	.000	0.0	48.1
ESE	3	87	.000	0.0	23.0
SSE	4	138	.059	5.1	44.9
SSW	5	131	.014	3.8	30.5
WSW	6	180	.029	3.3	22.2
WNW	7	75	.000	0.0	25.3
NNW	8	31	.000	0.0	29.0
Elevation (m)					
0-100	1	4	.000	-	-
101-200	2	2	.000	-	-
201-300	3	13	.000	0.0	0.0
301-400	4	30	.029	3.3	6.7
401-500	5	30	.000	0.0	13.3
501-600	6	27	.000	0.0	29.6
601-700	7	62	.000	0.0	19.4
701-800	8	86	.000	0.0	17.4
801-900	9	66	.000	0.0	33.3
901-1000	10	88	.031	2.3	28.4
1001-1100	11	284	.048	6.0	44.7
Bedrock					
intrusive (mainly quartz diorite and granodiorite)	1	311	.037	3.9	30.9
volcanic (andesite/basalt)	2	2	.000	-	-
metamorphic (granite gneiss and gneiss)	3	35	.077	8.6	57.1
Bedrock structure					
massive	1	17	.000	0.0	70.6
fractured	2	292	.032	3.4	29.5
sheared	3	1	.000	-	-
foliated	7	14	.192	21.4	92.9
Bedrock hardness					
average	3	5	-	-	-
hard	4	35	.075	5.7	40.0
very hard	5	284	.033	3.5	32.0

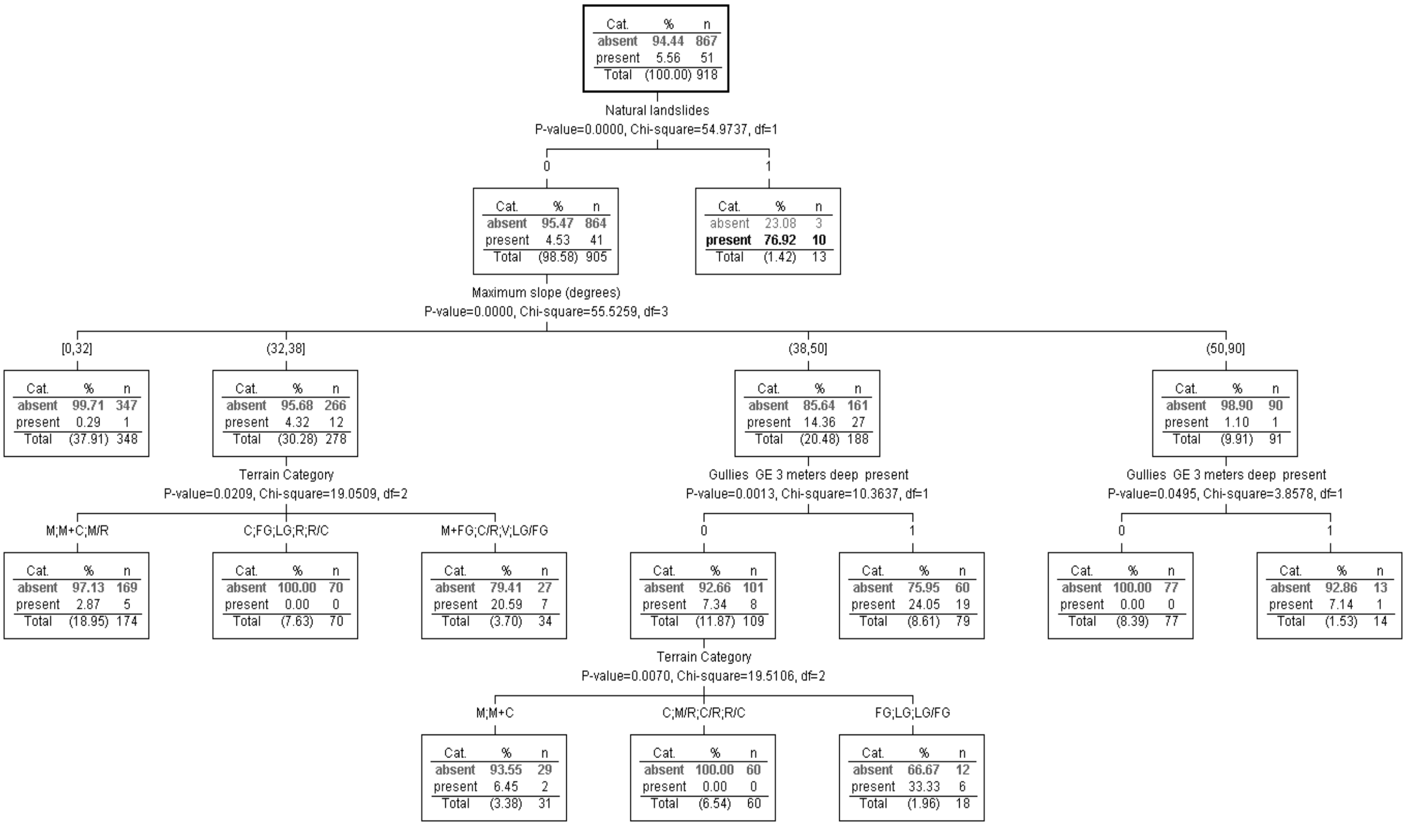
[1] *proportion symbols: / = dominant/subdominant; + = either component may be dominant or they may be equivalent.*

instability was considered.

A similar relationship was found when the measure of stability tested was the presence or absence of roadfill landslides >500 m^2 (Figure 9). In this case, CHAID selected gully gradient rather than gully depth as the most significant predictor variable, and then used maximum slope angle to further subdivide the gentler gully gradient limb of the segmentation tree. Gullies with channel gradients steeper than 25° had a higher likelihood of roadfill landslide activity than gullies with gradients less than 25°. In the case of gully gradients gentler than 25°, or in areas where gullies were absent (note: a '0°' gradient on the CHAID tree indicates an absence of gullies), roadfill landslide activity increased up to a maximum slope of 55° and then decreased (Figure 9). The reason for this decrease was unclear. However, we can speculate that these very steep slopes were dominated by bedrock, so any fill materials were composed of angular shot rock with a high angle of internal friction, and that in gullies these fills were supported by the gentle gradient floor of the gully. A second possibility is that roads were built on these steep slopes using full bench and end haul construction techniques. CHAID did not select road length as a predictor variable in this particular analysis.

When all field indicators of roadfill instability were used as the measure of road stability, CHAID was able to make a slightly

Figure 7. CHAID tree for all clearcut landslide presence – Leeward Coast Mountains



higher number of splits in the sample population (Figure 10). The first split was based on maximum slope angle. Intermediate slope categories were then split on the basis of either terrain category or bedrock structure (Figure 10). As we noted above, the incidence of roadfill instability generally increased with increasing slope angle but decreased when the maximum polygon slope angle exceeded 55°. In the 29° to 35° maximum slope angle category, a higher incidence of roadfill instability was associated with morainal and glaciofluvial materials. In the case of the 35° to 55° maximum slope angle category, massive, sheared, and foliated bedrock had a higher incidence of instability than areas of fractured bedrock or areas where bedrock was not exposed. There was no obvious explanation for this particular difference in the incidence of roadfill instability.

5.0 SUMMARY DISCUSSION

Several common themes run through this analysis. Landslides following both clearcutting and road building are more common in gullied terrain than elsewhere. Deeper gullies are more likely to experience landslide activity than shallow gullies. Steeper slopes tend to be more prone to landslides than gentler slopes, but the relationship is not always significant. There can be situations, more commonly with non-road landslides, where very steep, bedrock dominated slopes may experience less landslide activity than moderate and steeply sloping areas. Terrain units with deeper surficial materials, and in particular, morainal, glaciolacustrine and glaciofluvial materials, tend to be more vulnerable to landslide activity than areas dominated by bedrock and colluvial materials. However, these relationships are not always consistent. The presence of natural landslides, though rare in this particular data set, was associated with higher post-logging landslide activity.

Overall, both clearcut and road related landslide rates tend to be much lower in the Coast Mountains study watersheds than have been observed in other areas on the coast. For example, 3.7% of the terrain polygons in the Windward Zone and 1.3% of the terrain polygons in the Leeward Zone experienced clearcut landslides >500 m^2. By contrast, 17% of the polygons in study areas on the West Coast of Vancouver Island (Rollerson, Thomson and Millard, 1997) and 22% of the terrain polygons in a study in the Skidegate Plateau in the Queen Charlotte Islands (Rollerson, 1992,) experienced clearcut landslides >500 m^2 after logging. Mean clearcut landslide frequencies of 0.012 ls/ha in the Coast Mountains Windward Zone, and 0.008 ls/ha in the Coast Mountains Leeward Zone, are an order of magnitude lower than the Vancouver Island and Queen Charlotte Islands studies at 0.08 ls/ha, and 0.17 ls/ha respectively.

Finally, as a point of caution, we note that when using the presence of landslides within map polygons as a measure of landslide activity, for both clearcut landslides and road landslides, there is an expectation that the likelihood of a landslide will

Figure 8 CHAID tree for >500 m² roadfill landslide densities– Leeward Coast Mountains

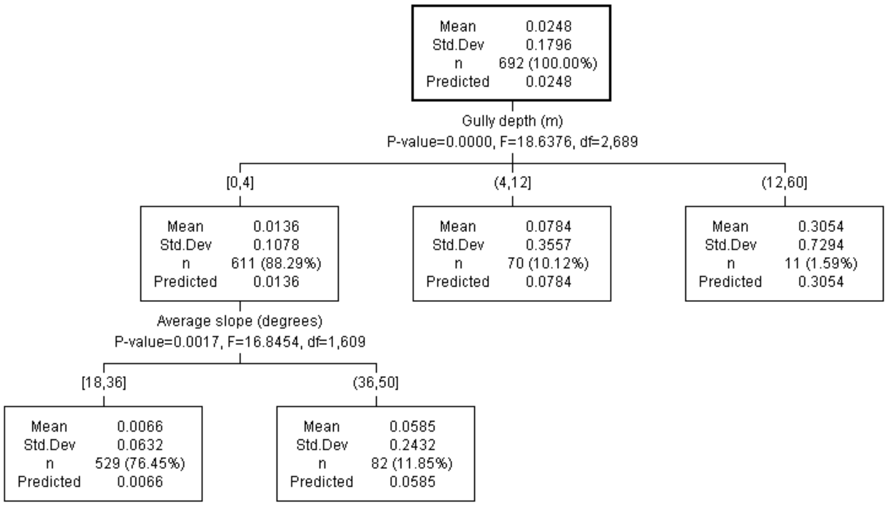


Figure 9. CHAID tree for >500 m² roadfill landslides presence – Leeward Coast Mountains

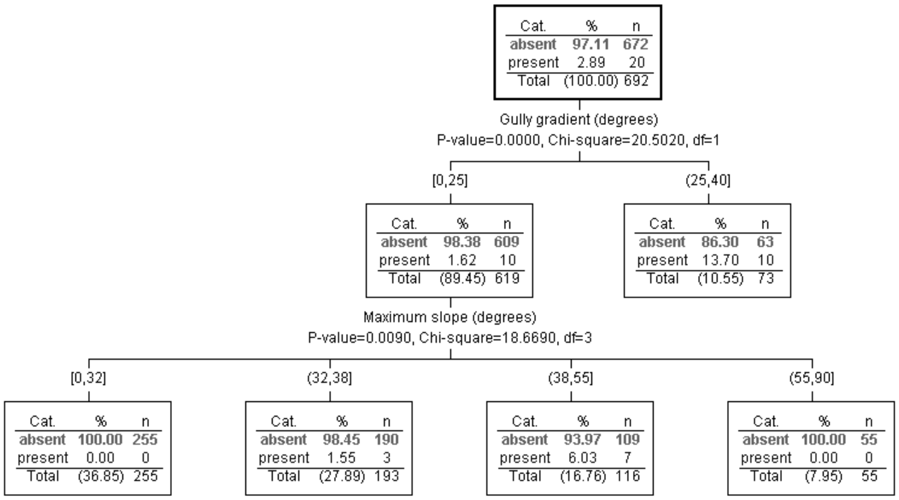
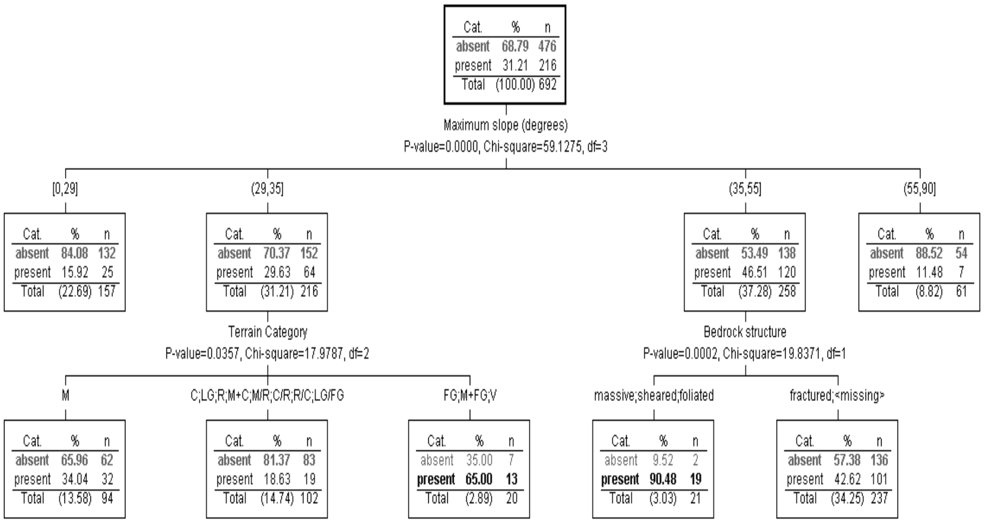


Figure 10. CHAID tree for all roadfill instability presence – Leeward Coast Mountains



increase as polygon size or road length increases. This means that as a measure of landslide activity, the presence or absence of landslides in terrain polygons will always be affected by polygon size or road length – that is, it is not a true probability. In the case of clearcut landslides, we found that the mean area of terrain polygons with landslides was significantly larger that the mean area of polygons without landslides (4.9 ha versus 3.5 ha respectively). There is no obvious way to avoid this issue, other than to use landslide density (e.g., ls/ha or ls/100m of road) as the preferred measure of landslide activity. However, landslide density values tend to be highly skewed because of the large number of terrain polygons with no landslides (i.e. the landslide density is zero for these samples), therefore the mean landslide density values documented in this report may not represent true mean values. However, this limitation aside, the reported landslide density values do serve as a useful indicator of expected landslide activity.

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