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Post-logging landslide rates in the Cascade Mountains, southwestern British Columbia

by

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Cover photo: Typical terrain in the Cascade Mountains, southwestern British Columbia.

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SUMMARY

Forestry operations in Coastal British Columbia occur across large tracts of land, often with terrain subject to post-logging landslides broadly distributed throughout the landscape. Some types of terrain have greater numbers of post-logging landslides than other terrain types. Terrain types that have high post-logging landslide rates often have high levels of risk to resources. Therefore, it is important to be able to accurately predict the expected post-logging landslide rate for areas designated for logging. Note that in this study the term "landslide rate" is used as either a spatial rate or as a percentage of samples with landslides – it does not imply a temporal rate. The term "landslide likelihood" is used in this study to indicate a prediction of expected post-logging landslide rates.

Methods of identifying terrain types susceptible to landslides are needed that are accurate and yet are rapid enough to be applied to extensive areas. Terrain attributes are landscape features that can be used to identify hillslopes susceptible to landslides. Terrain attribute studies produce statistically derived post-logging landslide rates by identifying significant terrain attributes or groups of terrain attributes associated with landslides in previously logged terrain. Logged hillslopes are divided into terrain polygons, which are small areas that have a consistent set of terrain attributes such as slope gradient, surficial material type, and slope morphology. Terrain attribute data is systematically collected in the field in conjunction with post-logging landslide data and analysed to identify those terrain attributes that are useful predictors of post-logging landslides. The method provides quantification of post-logging landslide rates – information that can be used to predict the likelihood of post-logging landslides in similar unlogged terrain. Such information is an important improvement over qualitative evaluation of landslide likelihood (e.g. undefined high, medium, and low likelihood of landslides).

Two types of landslide rates were used in this study. *Landslide presence* is the presence of one or more landslides within a terrain polygon. This study analysed landslide presence using only landslides >500 m^2 in area, as well as the presence of landslides of any size. *Landslide density* is the average number of landslides in a unit area. In this study, only >500 m^2 landslides were used to determine landslide density. Three post-logging landslide initiation locations were evaluated: clearcuts, road fills, and road cuts. The study used a combination of univariate and multivariate statistical procedures.

Clearcut areas in the Cascade Mountains of southwestern British Columbia were studied. A total of 617 terrain polygons were sampled, representing an aggregate area of 1808 ha. The mean polygon area was 2.9 ha, with a standard deviation of 2.7 ha and a range of 0.2 to 20.2 ha. Over 44 km of road were sampled. There were 83 >500 m^2 clearcut landslides, 39 >500 m^2 road fill landslides, and 24 >500 m^2 road cut landslides. A total of 54 (9%) of the 617 terrain polygons in the sample population had *>500 m^2 clearcut landslide presence*. Overall, the average *>500 m^2 clearcut landslide density* was 0.05 landslides per hectare (ls/ha).

Of the 317 terrain polygons in the study area with roads, 26 (8%) had *>500 m^2 road fill landslide presence*, and the average *>500 m^2 road fill landslide density* was 0.07 landslides/100 m of road length (ls/100m). Thirteen polygons (4%) had *>500 m^2 road cut landslide presence*, and the average *>500 m^2 road cut landslide density* was 0.04 ls/100 m.

The presence of gullies, and increasing depth of gullies, was strongly related to higher clearcut, road fill, and road cut landslides rates. Slope gradient was also related to clearcut, road fill, and road cut landslides. The presence of natural landslides, landscape position, slope morphology, and horizontal curvature were other attributes significantly related to landslide rates.

The use of terrain attributes is an important part of landslide assessment in Coastal British Columbia, both to analyze past occurrence of post-logging landslides and to predict the post-logging likelihood in similar unlogged terrain. This study reports observed post-logging landslide rates for clearcut and cable yarded forestry areas. Since terrain conditions are variable, and not all conditions may have been investigated in this study, a person experienced in terrain and landslide assessment should be consulted before applying these results to unlogged areas.

KEY WORDS

landslide rates, logging, terrain, Cascade Mountains.

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1.0 INTRODUCTION

Forestry operations in Coastal British Columbia occur across large tracts of land, often with terrain subject to post-logging landslides broadly distributed throughout the landscape. Post-logging landslide rates vary, depending on the type of terrain that is logged. As post-logging landslide rates increase, so too does the risk to resources. Therefore, it is important to be able to accurately predict the expected post-logging landslide rate for areas designated for logging. Note that in this study the term "landslide rate" is used as either a spatial rate or as a percentage of samples with landslides – it does not imply a temporal rate. The term "landslide likelihood" is used in this study to indicate a prediction of expected post-logging landslide rates.

Methods of identifying terrain susceptible to landslides are needed that are accurate and yet are rapid enough to be applied to extensive areas. Terrain attributes are features or characteristics of a specific, relatively uniform portion of a slope called a terrain polygon. Terrain attribute studies produce statistically derived post-logging landslide rates by identifying significant

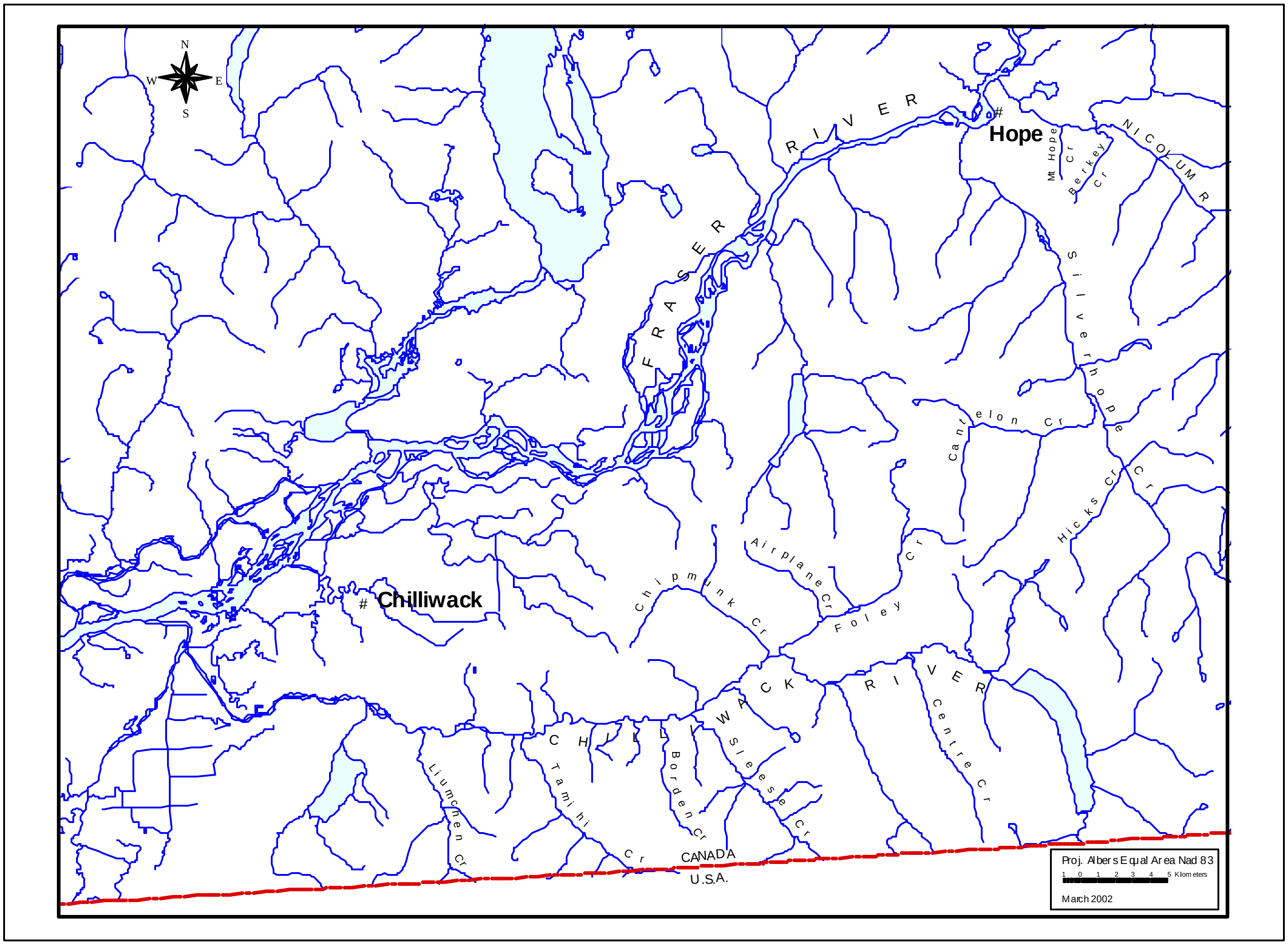

Figure 1. Location map, southwestern British Columbia.

terrain attributes or groups of terrain attributes associated with landslides in previously logged terrain. Using the assumption that unlogged terrain will have similar post-logging landslide rates as comparable terrain already logged, a quantitative estimate of post-logging landslide likelihood can be produced prior to logging. Since identification of these terrain attributes in the field (and to a certain extent on air photos and topographic maps) is usually easy, the method produces estimates of landslide rates in a relatively rapid manner.

This study examined logged terrain in the Cascade Mountains of southwestern British Columbia. This study is one of a series of terrain attribute studies that examines forestry-related landslide rates in Coastal British Columbia: Queen Charlotte Islands (Rollerson, 1992), West Coast of Vancouver Island (Rollerson et al, 1998), Coast Mountains (Rollerson et al, 2001), and southwest Vancouver Island (Rollerson et al, 2002).

The objectives of this study were to:

- characterize steep terrain that is susceptible to landslides following logging (clearcutting) and associated road building in the Cascade Mountains.
- develop terrain-based stability classifications for the Cascade Mountains that can be used to predict post-logging landslide likelihood.

2.0 STUDY AREA

2.1 AREA AND PHYSIOGRAPHY

The study area is located within the Skagit Range of the Cascade Mountains in south-western British Columbia, approximately 100 km east of Vancouver (Holland, 1964). It extends roughly southward from a line connecting the communities of Chilliwack and Hope (Figure 1). The study area is bounded on the north by the Fraser River, on the east by the Nicolum River and the east side of Silverhope Creek, on the south by the Canada-United States border, and on the west by the western boundary of the Liumchen Creek sub-basin.

Study sites were located within the Chilliwack River, Silverhope Creek and Nicolum Creek watersheds. Sub-basins of the Chilliwack River watershed in which study sites were located are Chipmunk, Airplane and Foley Creeks in the north and

Liumchen, Tamahi, Borden, Slesse, and Centre Creeks in the south. Within the mid reach of Silverhope Creek watershed, study sites were located in Cantelon and Hicks Creek sub-basins. In the western portion of lower Nicolum River watershed, study sites were selected in Mt. Hope and Berkey Creek sub-basins. With the exception of Borden Creek, the headwaters of the southern tributaries of the Chilliwack River watershed are within the United States.

Study sub-basins are rimmed by rugged peaks, some which support small hanging glaciers. Elevations range from 100 m at the mouth of Liumchen Creek sub-basin to 2439 m (Slesse Mountain) near the international border. The main valleys of the three major watersheds (Chilliwack, Silverhope, and Nicolum) tend to be U-shaped in cross section, having steep valley side walls with relatively wide and flat valley floors. Sub-basins of the major watersheds in general have steep valley sidewalls with narrow valley floors. Stream channels within sub-basins tend to be deeply incised into underlying bedrock and/or unconsolidated materials. Flood plains are narrow in width with relatively steep channel gradients.

During the Fraser Glaciation, the area was covered by a lobe of the Cordilleran Ice Sheet that originated from the Coast Mountains. At the glacial maximum a number of peaks within the study area were exposed as nunataks. During deglaciation, alpine or valley glaciers occupied individual local valleys. Post glacial modification of the landscape by mass wasting processes on valley sides and fluvial erosion in valley bottoms during the Holocene have resulted in the present landscape.

2.2 CLIMATE

The study area lies within the west coast maritime climatic zone, having relatively mild, wet winters with snow dominating at higher elevations. Typical of many coastal basins within mountainous terrain of the Pacific Northwest, two annual runoff peaks are common: one in the spring/summer due to snowmelt, and one in the autumn/winter due to prolonged and/or intense rainfall or rain on snow events. During the autumn/winter period, most precipitation falling above the 1000m elevation is snow. However, mild and wet Pacific weather systems occasionally result in intense rain at almost all elevations, and these rainstorms combine with snow melt to produce high flow runoff peaks of short duration.

Three biogeoclimatic zones are found within the study area: Coastal Western Hemlock, Mountain Hemlock, and at high elevations Alpine Tundra (Nuszdorfer and Beotger, 1993). The majority of the study sites lie within the Coastal Western Hemlock zone, however, a few sites in the southern and eastern portion of the study area fall within the Mountain Hemlock zone

2.3 BEDROCK GEOLOGY

The Cascade Mountains form a broad anticlinorum having an axial core composed of gneiss and granitic rock flanked by belts of folded and faulted but little metamorphosed sedimentary and volcanic rocks of late Paleozoic to mid Cretaceous age (Monger 1969). Skagit Range geology falls within the western flank of the Cascade anticlinorum. The study area is underlain by rocks composed of a number of differing lithologies that geographically form rough north-south discontinuous belts of rocks. Based on Monger (1989), in order of occurrence and location, from east to west, they include suites of rocks belonging to:

- The Hozameen Complex, present in the mid and upper Nicolum River and Silverhope River basins. Although it was present in the study area, none of the study locations were within the Hozameen Complex;
- The Chilliwack and Mt. Barr Batholiths in the upper Chilliwack River and mid Silverhope Creek basins;
- The Custer Gneiss, present in the mid Silverhope Creek and Chilliwack River basins;
- The Slollicun and Settler Schists, present in the mid Silverhope Creek and Chilliwack River basins;
- The Chilliwack Group, present in the mid and lower Chilliwack River basin;
- The Cultus Formation, present in the mid and lower Chilliwack River basin.

The Chilliwack and Mt. Barr Batholiths are composed of intrusive granodiorite and quartz diorite of Cretaceous to Tertiary age. The Custer Gneiss, and Slollicun and Settler Schists are metamorphic rock types derived from older rocks metamorphosed during Cretaceous and Tertiary periods. The Chilliwack Group is composed of volcanics, pelite, sandstone, conglomerate, and limestone of Permian and Pennsylvanian age. The Cultus Formation is composed of pelite and sandstone of Triassic and Jurassic age.

Intense deformation of these rocks occurred during the mid Cretaceous to early Tertiary periods and has resulted in the present structural pattern. During this time, sedimentary and volcanic rocks were folded, thrust and refolded to the northwest and west, undergoing faulting and minor metamorphism. The granitic rocks were intruded and emplaced during Tertiary to Miocene periods.

2.4 SURFICIAL GEOLOGY

Pleistocene and Holocene age deposits within the study area are typically unconsolidated sediments texturally composed of gravel, sand, silt, and/or clay, and combinations of these materials. These materials are of glacial, glaciofluvial, glaciolacustrine, or fluvial origin. Colluvial materials (composed of unconsolidated materials and/or bedrock) that originated from a number of slope processes including landslides are also represented.

At study sites the most common surficial materials encountered are glacial till (morainal deposits) and colluvium. Thick accumulations of these materials are found mainly along valley bottoms and lower valley sides. Thin and/or discontinuous mantles are present on mid and upper valley sides. Accumulations of colluvial materials are commonly found on upper valley sides, along the base of escarpments and at the mouths of steep gradient gullies. Colluvial materials composed of landslide deposits sometimes overlie older materials on mid and lower valley side slopes and valley floors.

Within the study area, the matrix texture of till is dependant upon the local bedrock source area. Where the up-valley source area is dominated by coarse grained granitic bedrock, till matrix textures tend to be sandy. Where the up valley source area is dominated by fine grained metamorphic and/or sedimentary bedrock, the till matrix textures tends to be silty. Matrix texture of colluvial materials likewise reflects source bedrock characteristics.

3.0 METHODOLOGY

3.1 SAMPLING DESIGN

Within the Chilliwack River and Silverhope Creek basins, almost all accessible logged areas, ranging in age from 6 to 15 years following logging, were examined. Two small watersheds in the Nicolum watershed were added as they were adjacent to the Silverhope drainage. The lower age limit of 6 years after logging was established so that the areas had time to experience a number of large storms after logging and to give adequate time for root strength loss to occur. The upper age limit was established because increasing tree height and crown closure in plantations older than 15 years tend to mask local terrain features, including small landslides, making collection of accurate data difficult. For the sake of efficiency, areas with slope gradients less than 20° were excluded from the study, because previous studies have shown they rarely have post-logging landslides. Each study area was mapped at a scale of 1:20,000 using 1:15,000 to 1:20,000 scale airphotos and the BC Terrain Classification System (Howes and Kenk, 1997). Each terrain polygon was visited in the field. A follow-up survey was carried out six years after the original study to document any subsequent landslides.

All study areas were clearcut, almost always using cable systems to yard logs to roadside. Almost all roads were conventionally constructed, with cuts and fills. In some very steep locations full-bench roads were constructed.

3.2 DATA COLLECTION

For each terrain polygon, the following terrain attributes were recorded:

- Slope gradient (in degrees), recorded as maximum, average, and minimum slope gradients;
- Natural landslides >500 m^2 in slope – not planimetric – area (absent or present);
- Minor natural landslides <500 m^2 in slope area (absent or present);
- Landscape position (four categories);
- Slope morphology (five categories);
- Terrain category (ten groupings of surficial materials);
- Horizontal curvature (four categories);
- Soil drainage (four categories);
- Slope aspect (divided into octants);
- Elevation (divided into five ranges of elevations);
- Bedrock formation (five categories, identified from 1:250,000 geological map [Monger, 1989], and if possible, confirmed in the field. Insufficient numbers of field observations of lithology and bedrock structure were collected to make analysis of these variables possible);
- Surficial material depth (in metres);
- Gully depth (in metres);
- Polygon slope area (in ha), using planimetric polygon area (digitized from the air photos using mono-restitution), and then adjusted by average slope gradient to estimate slope area;
- Road length (in metres).

For each terrain polygon, the following post-logging landslide characteristics were recorded:

- The number of >500 m^2 landslides that initiated within the clearcut area (slope area – not planimetric area – for all landslide sizes). Field verification indicated that 500 m^2 landslides in recent clearcuts were consistently identified on 1:15,000 scale air photos by experienced terrain mappers. Landslides smaller than 500 m^2 were more difficult to identify on a consistent basis on air photos;
- The number of >500 m^2 landslides initiating within road fills;
- The number of >500 m^2 landslides initiating within or directly above road cuts;
- The presence or absence of one or more <500 m^2 landslides in clearcut areas. Since smaller landslides were difficult to consistently identify, they were not individually enumerated;
- The presence of one or more <500 m^2 landslides associated with road fills. In addition, signs of potential road fill instability such as tension cracks and fill slope settlement were also recorded;
- The presence of one or more <500 m^2 landslides associated with road cuts.

3.3 DATA ANALYSIS

Two specific post-logging landslide rates were used in the analysis*: landslide presence* and *landslide density*.

Landslide presence is the presence of the initiation point of one or more post-logging landslides within a terrain polygon. The analysis reports the percentage of polygons with landslides present. Landslide presence was evaluated using four criteria:

1. Only landslides >500 m^2 were used as the dependent variable. This outcome applies to clearcut landslides, road fill landslides and road cut landslides;
2. For clearcut areas, the presence of landslides of any size was used as an additional dependent variable;
3. For road fills, the presence of any sign of instability was used as a second dependent variable. This measure included landslides of any size, tension cracks and fill slope settlement;
4. For road cuts, the presence of landslides of any size was used as a second dependent variable.

Landslide density is the average number of landslides within a unit area or along a unit length of road. Landslide density considered only landslides >500 m^2 since smaller landslides were not individually enumerated. For clearcut areas, landslide density was measured as landslides per hectare (ls/ha). For roads, landslide density was measured as landslides per 100 of road length (ls/100 m).

Some readers may find the inverse expression of landslide density easier to understand. As an example, if a terrain type has 0.2 ls/ha, then on average one landslide will occur in every five ha. Similarly, if road segments in a specific terrain type have a road fill landslide density of 0.2 ls/100 m, then on average one road fill landslide will occur in every 500 m of road length.

This approach resulted in nine landslide rates used in the analysis:

Clearcut landslide rates-

1. percentage of polygons with *>500 m^2 clearcut landslide presence*
2. *>500 m^2 clearcut landslide density (ls/ha)*
3. percentage of polygons with *any size of clearcut landslide presence*

Road fill landslide rates-

4. percentage of polygons with *>500 m^2 road fill landslide presence*
5. *>500 m^2 road fill landslide density (ls/100 m)*
6. percentage of polygons with *any road fill instability presence*

Road cut landslide rates-

7. percentage of polygons with *>500 m^2 road cut landslide presence*
8. *>500 m^2 road cut landslide density (ls/100 m)*
9. percentage of polygons with *any road cut landslide presence.*

For each terrain attribute, the nine landslide rates were determined. Chi-square tests were used to test for significant differences in the presence or absence of landslides. The Kruskal-Wallis test was used when testing for significant differences in landslide density. If the statistical test showed significance, then at least some of the categories within a terrain attribute were significantly different from one another, but not necessarily all categories were different. For each test, a significance level of $P \leq 0.05$ was used.

Clearcut landslide density was weighted by polygon area to reduce any bias that could result from variation in polygon size. Similarly, road fill and road cut landslide density was weighted by road length. Landslide density is considered a more accurate landslide rate measurement than landslide presence because it accounts for individual landslides, rather than the presence of one or more landslides, and it is weighted by polygon area or road length. For this reason, most of the results and discussion sections of this report refer to landslide density rather than landslide presence.

Multivariate analysis was also carried out. Using CHAID (Chi-squared Automatic Interaction Detector), individual terrain polygons that had a similar post-logging landslide rate were grouped into multi-factor terrain categories. CHAID uses a non-parametric, multivariate procedure known as segmentation modeling (Magidson J./SPSS Inc, 1993). The procedure divides a sample population into two or more distinct groups based on the best predictors of a dependent variable. Groups are further subdivided if CHAID identifies additional significant variables. Segments defined by the analysis do not overlap. Both dependent and predictor variables are treated as categorical variables. At each segmentation level, the procedure merges categories of a predictor variable that are not significantly different at each segmentation level. The CHAID analysis of landslide density used weighted data. The analysis produces a tree diagram that identifies the most significant variables and presents statistics for each separate group or segment of the dependent variable. These categories can form the basis of a terrain stability classification that estimate the likelihood of landslides occurring after clearcut logging and associated road building.

4.0 RESULTS

A total of 617 terrain polygons were mapped and sampled in the Cascade Mountains on slopes $\geq$20°, representing an aggregate area of 1808 ha (Table 1). The mean polygon area was 2.9 ha, with a standard deviation of 2.7 ha and a range of 0.22 to 20.2 ha. The median polygon size was 2.1 ha. Both polygons with *>500 m^2 clearcut landslide presence* and polygons without landslides had a mean polygon area of 2.9 ha. Total road length within the study polygons was 44.5 km. The data were collected in 1994, and in 2000 a follow-up helicopter reconnaissance identified an additional five clearcut and two road fill landslides that

Table 1. Summary of data collection, by watersheds

Watershed	Number of polygons	Total polygon area (ha)	Road length (km)	Number of >500 m^2 clearcut landslides	Number of >500 m^2 road fill landslides	Number of >500 m^2 road cut landslides
Airplane + Chipmunk	104	263	5.7	17	4	0
Berkey + Mt. Hope	64	296	10.2	0	3	1
Borden	106	163	3.8	14	1	4
Cantelon + Hicks	34	80	2.3	6	1	0
Centre	63	207	4.6	13	16	8
Chilliwack	28	87	1.9	7	2	2
Foley	120	296	6.1	9	3	7
Liumchen	9	40	0.8	1	2	0
Slesse	56	193	4.9	2	2	0
Tamahi	33	184	4.3	14	5	2
Total	**617**	**1808**	**44.5**	**83**	**39**	**24**

were not present in 1994. Including the 2000 data, there were a total of 146 >500 m^2 landslides: 83 >500 m^2 clearcut landslides, 39 >500 m^2 road fill landslides, and 24 >500 m^2 road cut landslides.

4.1 UNIVARIATE TERRAIN ATTRIBUTE ANALYSIS

Univariate analysis of the terrain attribute data is used to describe general results and to draw general conclusions. However, there may be correlations among the variables affecting the results. As an example, steeper slopes may be associated with certain terrain types. If a terrain type had a high landslide rate, it may actually be a result of steeper slopes, not terrain type. In addition, since the study sampled only the available logged terrain units, there were some variable categories that had a limited number of samples. Results for categories that have limited sample numbers should be interpreted cautiously.

4.1.1 CLEARCUT LANDSLIDES (TABLES 2 AND 3)

The 83 >500 m^2 clearcut landslides occurred in 54 (9%) of the 617 terrain polygons. Overall, the average *>500 m^2 clearcut land-*

Table 2. Comparison of terrain attributes with clearcut landslide rates.

Terrain Attribute	Significance of terrain attribute (P-value)		
	>500 m^2 clearcut landslide presence[1]	*>500 m^2 clearcut landslide density*[2]	*Any clearcut landslide presence*[1]
Slope gradient	ns	0.008	0.004
Natural landslides	0.001	<0.001	0.008
Minor natural landslides	ns	Ns	0.038
Landscape position	<0.001	<0.001	<0.001
Slope morphology	0.007	<0.001	<0.001
Terrain category	0.004	0.002	0.004
Horizontal curvature	0.009	0.005	<0.001
Soil drainage	ns	ns	ns
Slope aspect	0.045	ns	ns
Elevation	ns	ns	0.001
Bedrock formation	ns	ns	0.025
Surficial material depth	ns	ns	ns
Gully depth	<0.001	<0.001	<0.001

(1) Chi-square test
(2) Kruskal-Wallis test
(ns = not significant)

Table 3. Terrain attributes - clearcut landslides summary statistics.

Terrain Attribute	n	*>500 m^2 clearcut landslide presence (%)*	*Average >500 m^2 clearcut landslide density (#/ha)*	*Any clearcut landslide presence (%)*
Slope gradient (°)				
20 – 25	103	4.9	0.06	16
26 – 30	170	7.1	0.03	19
31 – 35	195	8.7	0.04	22
36 – 40	97	13	0.06	21
41 – 45	38	13	0.06	40
>45	7	14	0.03	57
Natural landslides				
absent	606	8.2	0.04	21
present	11	36	0.18	55
Minor natural landslides				
absent	613	8.7	0.05	22
present	5	20	0.05	60
Landscape position				
upper slope	169	1.8	0.01	9.5
mid slope	344	9.8	0.05	25
lower slope	95	15	0.08	32
escarpment	5	60	0.47	80
headwater	3	-[1]	-	-
Slope morphology				
uniform	487	7.4	0.04	16
benchy	10	0.0	0.00	10
dissected (>1 gully)	12	17	0.02	25
faceted	4	-	-	-
irregular	34	5.9	0.01	15
single gullies	67	21	0.27	67
Terrain category[2]				
Morainal blankets/veneers	180	14	0.10	31
Morainal veneers	6	33	0.22	33
Colluvial blankets/veneers	56	1.8	0.01	7.1
Colluvial veneers	51	0.0	0.00	9.8
Glaciofluvial & moraine/F^G	3	-	-	-
Rock & rock/colluvial	46	11	0.03	24
Morainal+colluvial blankets	91	11	0.05	25
Morainal+colluvial	75	4.0	0.02	15
Morainal+rock	39	5.1	0.02	28
Colluvial/rock	70	7.1	0.04	20
Horizontal curvature				
Concave	130	16	0.11	48
Convex	73	8.1	0.03	14
Straight	410	6.6	0.03	15
Complex	2	-	-	-
Soil drainage				
Rapidly	161	5.6	0.03	19
Well	401	9.4	0.05	22
Moderately well	41	12	0.07	29
Imperfectly	9	11	0.02	33
Slope aspect				
NNE	71	2.8	0.03	17
ENE	69	8.6	0.05	23
ESE	92	14	0.05	28
SSE	69	4.3	0.02	16
SSW	55	18	0.12	22
WSW	74	7.8	0.05	17
WNW	85	9.4	0.04	26
NNW	90	7.7	0.05	29
Elevation (m)				
≤500	23	8.7	0.03	39
501 – 1000	188	11	0.05	30
1001 – 1500	393	7.8	0.04	18
1501 – 2000	9	0.0	0.00	0.0
Bedrock formation				
Chilliwack Group	261	6.5	0.05	23
Cultus Formation	159	11	0.06	23
Gneiss	34	18	0.08	24
Slollicun and Settler Schists	36	14	0.07	36
Tertiary Granitics	127	7.1	0.03	13
Surficial material depth (m)				
<0.5	32	22	0.09	34
0.6 – 1.0	136	4.4	0.02	16
1.1 – 1.5	0	-	-	-
1.6 – 2.0	105	1.0	0.00	8.6
2.1 – 2.5	0	-	-	-
2.6 – 3.0	108	4.6	0.02	23
>3.0	225	15	0.09	28
Gully depth (m)				
No gullies	482	5.8	0.03	13
0 – ≤3	83	13	0.07	44
3.1 – 6	28	17	0.09	69
6.1 – 9	13	21	0.29	79
>9	12	57	0.39	64

1) "-": landslide rates are not reported for sample populations <5
2) Proportion symbols for terrain categories: / indicates dominant/subdominant; + indicates either component may be dominant or they may be equivalent.

slide density was 0.05 ls/ha. If *any size of clearcut landslide presence* is considered, then 134 (22%) of the terrain polygons experienced one or more clearcut landslides.

The presence of natural landslides, landscape position, slope morphology, terrain category, horizontal curvature, and gully depth all showed a significant effect on clearcut landslide rates, no matter which clearcut landslide rate was considered (Table 2). With reference to Table 3:

- Polygons with natural landslides >500 m^2 in size had an average *>500 m^2 clearcut landslide density* of 0.18 ls/ha, in comparison to all other polygons that had 0.04 ls/ha
- Escarpment slopes had a much higher average landslide density (0.47 ls/ha) compared to the other landscape positions (0.01 – 0.08 ls/ha), however note that there were only 5 escarpment samples.
- Single gullies had 0.27 ls/ha, by far the highest landslide density of any slope morphology. Dissected slopes showed the second highest landslide rates for both *>500 m^2 clearcut landslide presence* and *any size of clearcut landslide presence*, but this was not evident for *>500 m^2 clearcut landslide density*.
- Slopes with pure morainal veneers had the highest clearcut landslide rates of any terrain type, however there were only six samples. Slopes with a combination of morainal blankets and morainal veneers had the next highest landslide rates.
- Concave slopes had higher landslide rates than convex or straight slopes.
- As gully depth increased, so too did landslide rates. Polygons without gullies had a landslide density of 0.03 ls/ha, gullies ≤6 m deep had 0.07 – 0.09 ls/ha, gullies between 6 and 9 m deep had 0.29 ls/ha, and gullies deeper than 9 m had 0.39 ls/ha.

In other terrain attribute studies from Coastal BC, clearcut landslide rates consistently increase as slope gradient increases from 20° to about 40°. This pattern was evident in this study in *>500 m^2 clearcut landslide presence* (Table 3); however, the differences were not significant (Table 2). The same pattern was evident for *any size of clearcut landslide presence*, where the differences were significant. However, when *>500 m^2 clearcut landslide density* is examined, polygons with gradients from 20 – 25° had 0.06 ls/ha, as did slopes from 31 – 45°, while all other slope gradients had lower landslide densities (Table 3). Three very small gullied polygons (≤0.7 ha), with sidewall slope angles ≥26°, but average slope gradients from 20 – 25°, each had three >500 m^2 clearcut landslides, and these samples strongly affected these particular landslide density results. If these three samples are excluded, the remaining polygons in the 20 – 25° slope gradient class had an average *>500 m^2 clearcut landslide density* of 0.01 ls/ha.

4.1.2 ROAD FILL LANDSLIDES (TABLES 4 AND 5)

The 39 >500 m^2 road fill landslides occurred in 26 (8%) of the 317 terrain polygons in the study area with roads. The average *>500 m^2 road fill landslide density* was 0.07 ls/100 m of road length. If *any road fill instability presence* is considered, then 113 (36%) of the terrain polygons had unstable or potentially unstable road sections.

Only one terrain attribute significantly affected all road fill landslide rate measures – slope gradient (Table 4). Road fill landslide rates increased with increasing slope gradient, with slopes from 36 – 40° having had the greatest landslide density (0.16 ls/100 m, Table 5). Slopes steeper than 40° had slightly lower road fill landslide rates than the slopes from 36 – 40°.

The presence of natural landslides, landscape position, horizontal curvature, and gully depth all had a significant effect on *>500 m^2 road fill landslide presence* and *>500 m^2 road fill landslide density* (Table 4). With reference to Table 5:

- Road fill landslide density averaged 0.07 ls/100 m for polygons without natural landslides, but increased to 0.29 ls/100 m for polygons that had natural landslides.
- Roads on lower landscape positions had higher road fill landslide rates compared with roads on mid slope and escarpment positions.
- Concave slopes had higher road fill landslide rates than convex or straight slopes.
- The deepest gullies (>9 m) had a much higher road fill landslide density (0.75 ls/100 m) than shallower gullies or polygons without gullies (≤0.22 ls/100 m).

Slope aspect was significant for both *>500 m^2 road fill landslide presence* and *any road fill instability presence* (Table 4). Slopes in the SSW octant had higher landslide rates than other slope aspects (Table 5).

Table 4. Comparison of terrain attributes with road fill landslide rates.

Terrain Attribute	Significance of terrain attribute (P-value)		
	>500 m^2 road fill landslide presence^1	*>500 m^2 road fill landslide density^2*	*Any road fill instability presence^1*
Slope gradient	0.031	<0.001	0.002
Natural landslides	0.024	<0.001	ns
Minor natural landslides	ns	<0.001	ns
Landscape position	<0.001	0.002	ns
Slope morphology	ns	ns	ns
Terrain category	ns	ns	ns
Horizontal curvature	0.021	<0.001	ns
Soil drainage	ns	ns	ns
Slope aspect	ns	0.028	0.045
Elevation	ns	ns	0.024
Bedrock formation	ns	ns	0.023
Surficial material depth	ns	ns	ns
Gully depth	<0.001	<0.001	ns

(1) Chi-square test
(2) Kruskal-Wallis test
(ns = not significant)

4.1.3 ROAD CUT LANDSLIDES (TABLES 6 AND 7)

The 24 >500 m^2 road cut landslides occurred in 13 (4%) of the 317 terrain polygons in the study area with roads. The average *>500 m^2 road cut landslide density* was 0.04 ls/100 m. If *any road cut landslide presence* is considered then 84 (26%) of the terrain polygons experienced landslides.

Slope gradient, the presence of natural landslides, landscape position, horizontal curvature, and gully depth had a significant effect on all road cut landslide rates (Table 6). With reference to Table 7:

- There was a consistent increase in road cut landslide rates as slope gradient increased. Unlike road fill landslides (Table 5), this increase in landslide rates did not reach a peak for slopes from 36 – 40°, but was a maximum for slopes from 40 – 45° (0.21 ls/100 m).
- Similar to road fill landslides (Table 5), there were greater road cut landslide rates for roads located on lower landscape posi-

Table 5. Terrain attributes - road fill landslides summary statistics.

Terrain Attribute	n	*>500 m^2 road fill landslide presence (%)*	*>500 m^2 road fill landslide density (ls/100 m)*	*Any road fill instability presence (%)*
Slope gradient (°)				
20 – 25	57	1.8	0.02	23
26 – 30	105	7.6	0.08	29
31 – 35	100	7.0	0.05	42
36 – 40	41	20	0.16	59
41 – 45	10	20	0.14	40
>45	2	-^{1}	-	-
Natural landslides				
absent	309	7.8	0.07	35
present	6	33	0.29	67
Minor natural landslides				
absent	312	8.0	0.07	36
present	3	-	-	-
Landscape position				
upper slope	0	-	-	-
mid slope	98	2.0	0.02	39
lower slope	166	12	0.10	35
escarpment	47	4.3	0.03	32
headwater	3	-	-	-
Slope morphology				
uniform	237	7.6	0.06	35
benchy	6	17	0.15	67
dissected (>1 gully)	11	9.1	0.03	36
faceted	1	-	-	-
irregular	18	5.6	0.04	22
single gullies	40	12	0.35	40
Terrain category				
Morainal blankets/veneers	93	12	0.10	34
Morainal veneers	4	-	-	50
Colluvial blankets/veneers	31	3.2	0.02	23
Colluvial veneers	25	4.0	0.03	48
Glaciofluvial & moraine/F^G	1	-	-	-
Rock & rock/colluvial	17	18	0.14	41
Morainal+colluvial blankets	57	11	0.13	33
Morainal+colluvial	40	7.5	0.05	40
Morainal+rock	25	4.0	0.03	32
Colluvial/rock	24	0.0	0.0	46
Horizontal curvature				
Concave	74	15	0.21	39
Convex	36	0.0	0.00	36
Straight	204	7.4	0.05	34
Complex	0	-	-	-
Soil drainage				
Rapidly	68	5.9	0.04	43
Well	219	8.7	0.08	34
Moderately well	23	13	0.11	39
Imperfectly	2	-	-	-
Slope aspect				
NNE	34	5.9	0.08	24
ENE	40	10	0.07	42
ESE	47	11	0.06	38
SSE	31	6.4	0.04	32
SSW	31	16	0.24	61
WSW	40	15	0.15	40
WNW	41	2.4	0.02	29
NNW	44	2.3	0.02	27
Elevation (m)				
≤500	7	0.0	0.00	14
501 – 1000	96	7.3	0.06	25
1001 – 1500	207	9.2	0.08	42
1501 – 2000	5	0/0	0.00	40
Bedrock formation				
Chilliwack Group	123	7.3	0.06	29
Cultus Formation	82	5.4	0.05	47
Gneiss	18	5.6	0.04	33
Slollicun and Settler Schists	11	11	0.10	16
Tertiary Granitics	80	12	0.10	41
Surficial material depth (m)				
≤0.5	9	0.0	0.00	44
0.6 – 1.0	62	6.4	0.06	40
1.1 – 1.5	1	-	-	-
1.6 – 2.0	54	5.6	0.03	39
2.1 – 2.5	51	9.8	0.08	33
2.6 – 3.0	135	9.6	0.09	32
>3.0				
Gully depth (m)				
No gullies	243	5.4	0.04	33
0 – ≤3	38	21	0.18	47
3.1 – 6	20	5	0.03	25
6.1 – 9	6	17	0.22	67
>9	8	38	0.75	62

1) “-”: landslide rates are not reported for sample populations <5
2) Proportion symbols for terrain categories: / indicates dominant/subdominant; + indicates either component may be dominant or they may be equivalent.

tions compared with other landscape positions.

- Similar to road fill landslides, there were greater road cut landslide rates for concave slopes than convex or straight slopes.
- Both *>500 m^2 road cut landslide presence* and *>500 m^2 road cut landslide density* showed gullies that were >6 m in depth had much higher landslide rates than gullies that were <6 m deep, or polygons that had no gullies at all. For *any road cut landslide presence*, all polygons that had gullies showed a greater landslide presence rate compared with polygons without gullies (Table 7).

Slope morphology was a significant factor for both *>500 m^2 road cut landslide density* and *any road cut landslide presence* (Table 6). In both cases single gullies showed the highest landslide rate compared to other slope morphologies (Table 7).

Surficial material depth was a significant factor for both *>500 m^2 road cut landslide density* and *any road cut landslide presence* (Table 6). Both measures showed that surficial materials deeper than 3 m had the greatest road cut landslide rates, and *any road cut land-*

Table 6. Comparison of terrain attributes with road cut landslide rates.

Terrain Attribute	Significance of terrain attribute (P-value)		
	>500 m^2 road cut landslide presence[1]	*>500 m^2 road cut landslide density (ls/100 m)*[2]	*Any road cut landslide presence*[1]
Slope gradient	0.031	<0.001	0.040
Natural landslides	0.024	<0.001	ns
Natural landslides	<0.001	<0.001	0.001
Minor natural landslides	ns	ns	ns
Landscape position	0.032	0.020	0.021
Slope morphology	ns	<0.001	0.003
Terrain category	ns	ns	ns
Horizontal curvature	0.023	<0.001	0.005
Soil drainage	ns	ns	ns
Slope aspect	ns	ns	0.010
Elevation	ns	ns	<0.001
Bedrock formation	ns	ns	<0.001
Surficial material depth	ns	0.009	<0.001
Gully depth	<0.001	<0.001	0.004

(1) Chi-square test
(2) Kruskal-Wallis test
(ns = not significant)

Table 7. Terrain attributes - road cut landslides summary statistics.

Terrain Attribute	n	*>500 m^2 road cut landslide presence (%)*	*>500 m^2 road cut landslide density (ls/100 m)*	*Any road cut landslide presence (%)*
Slope gradient (°)				
20 – 25	57	3.5	0.02	12
26 – 30	105	3.8	0.03	23
31 – 35	100	1.0	0.01	34
36 – 40	41	9.8	0.14	32
41 – 45	10	20	0.21	40
>45	2	-[1]	-	-
Natural landslides				
absent	309	3.6	0.03	25
present	6	33	0.57	83
Minor natural landslides				
absent	312	4.2	0.04	26
present	3	-	-	-
Landscape position				
upper slope	0	-	-	-
mid slope	98	0.0	0.00	16
lower slope	166	7.2	0.07	31
escarpment	47	2.1	0.02	28
headwater	3	-	-	-
Slope morphology				
uniform	237	3.4	0.04	24
benchy	6	0.0	0.00	17
dissected (>1 gully)	11	0.0	0.00	0.0
faceted	1	-	-	-
irregular	18	0.0	0.00	17
single gullies	40	12.5	0.22	50
Terrain category				
Morainal blankets/veneers	93	6.6	0.09	33
Morainal veneers	4	-	-	-
Colluvial blankets/veneers	31	3.2	0.02	26
Colluvial veneers	25	0.0	0.00	28
Glaciofluvial & moraine/F^G	1	-	-	-
Rock & rock/colluvial	17	0.0	0.00	5.9
Morainal+colluvial blankets	57	5.3	0.04	30
Morainal+colluvial	40	0.0	0.00	15
Morainal+rock	25	8.0	0.10	32
Colluvial/rock	24	4.2	0.03	25
Horizontal curvature				
Concave	74	9.5	0.15	40
Convex	36	0.0	0.00	28
Straight	204	2.9	0.03	21
Complex	0	-	-	-
Soil drainage				
Rapidly	68	4.4	0.03	29
Well	219	3.2	0.04	53
Moderately well	23	13	0.14	9
Imperfectly	2	-	-	-
Slope aspect				
NNE	34	2.9	0.02	8.8
ENE	40	2.5	0.02	20
ESE	47	2.1	0.01	15
SSE	31	3.2	0.10	26
SSW	31	9.7	0.12	42
WSW	40	7.5	0.07	40
WNW	41	2.4	0.02	34
NNW	44	4.5	0.05	30
Elevation (m)				
≤500	7	0.0	0.00	29
501 – 1000	96	5.2	0.07	41
1001 – 1500	207	3.9	0.03	18
1501 – 2000	5	-	-	-
Bedrock formation				
Chilliwack Group	123	2.4	0.03	24
Cultus Formation	82	4.0	0.07	28
Gneiss	18	0.0	0.00	0.0
Slollicun and Settler Schists	11	5.3	0.05	68
Tertiary Granitics	80	7.4	0.05	25
Surficial material depth (m)				
≤0.5	9	0.0	0.00	11
0.6 – 1.0	62	0.0	0.00	13
1.1 – 1.5	1	-	-	-
1.6 – 2.0	54	1.9	0.01	17
2.1 – 2.5	51	2.0	0.02	22
2.6 – 3.0				
>3.0	135	8.1	0.09	38
Gully depth (m)				
No gullies	243	2.9	0.03	22
0 – ≤3	38	2.6	0.02	34
3.1 – 6	20	5.0	0.08	50
6.1 – 9	6	33	0.67	37
>9	8	25	0.23	38

1) "-": landslide rates are not reported for sample populations <5
2) Proportion symbols for terrain categories: / indicates dominant/subdominant; + indicates either component may be dominant or they may be equivalent.

slide presence showed an increasing landslide rate as surficial material depth increased (Table 7).

4.2 MULTIVARIATE ANALYSIS

CHAID trees contain a large amount of information, and until readers are familiar with the structure and content of the trees, the trees may be difficult to interpret. Readers should focus on the following features when referring to the results of the multivariate analysis presented in the CHAID trees, Figures 2 to 10:

- For CHAID trees of *landslide presence* (Figures 2, 4, 5, 7, 8, and 10), each box shows the total number of polygons (n) within that sample category, and the percentage of polygons within that category that had landslides present. For reporting purposes, the percentages have been rounded to the nearest whole number.
- For CHAID trees of *landslide density* (Figures 3, 6 and 9), each box shows the weighted sample size (n) and the mean (average) landslide density. For clearcut landslide density (Figure 3), the sample size approximates the number of hectares within that category. For road fill or road cut landslide density (Figures 6 and 9), the sample number approximates the number of 100 m road length segments. The predicted values at the bottom of each box are not relevant to this analysis.

Using Figure 2 as an example:

- The topmost line of text shows the landslide rate that is analysed, “Presence of clearcut landslide >500 m^2”. The top box represents the entire study sample, and shows the total sample number (n = 617), and the number and percentage of samples with landslides present (n = 54 and 8.75%, respectively).
- Below the top box (and at each subsequent level) is the terrain attribute that was most significant – in this case the first attribute is gully depth class. Underneath the terrain attribute is statistical information – the P-value, Chi-square statistic, and the degrees of freedom (df). Those readers familiar with statistics may wish to use this information; however, readers not familiar with statistics can ignore this information.
- Below the statistical information, the entire data set is split into three groups: “No gullies”, “0-3m; 3-6m; 6-9m”, and “>9m”. The three classes of gully depth from 0 to 9 m deep were grouped together in one box because CHAID did not identify any significant difference between these groups. Fif-

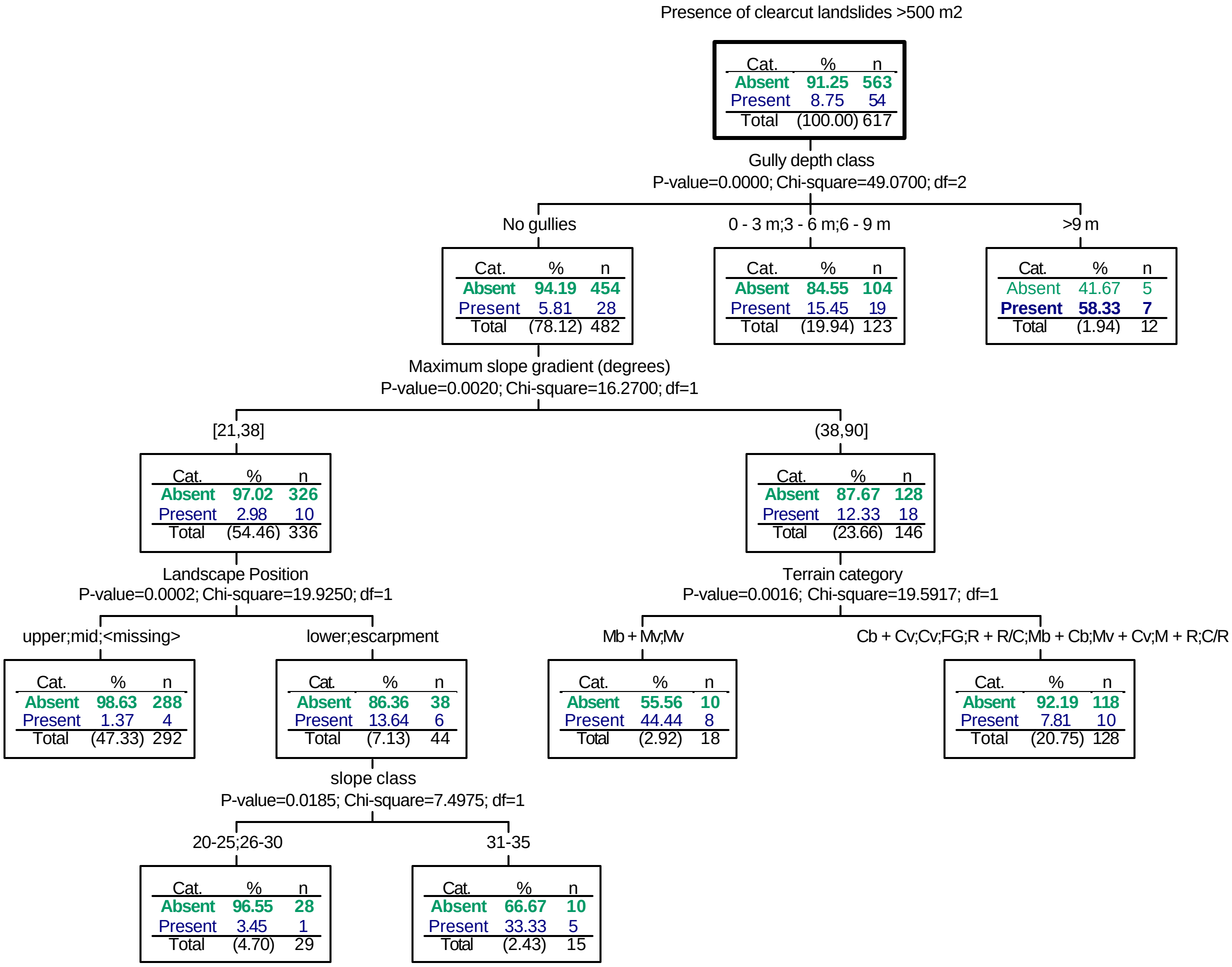

Figure 2. CHAID tree for *>500 m^2 clearcut landslide presence.*

teen per cent of the 123 polygons with gullies from 0 to 9 m in depth had >500 m^2 clearcut landslides present, compared with 6% for polygons without gullies and 58% for polygons with gullies deeper than 9 m.

- Each CHAID tree has partial terrain attribute categories (boxes that are further split), and final terrain attribute categories (boxes that are not further split). When combined, all of the final terrain attribute categories form the basis of a terrain classification system, with each final terrain attribute category having an associated landslide rate. As an example from Figure 2, just over 1% (rounded from 1.37%) of polygons with all of the following features had *>500 m^2 clearcut landslide presence*: non-gullied slopes, maximum slope gradients 21– 38°, and an upper or mid slope position. Table 8 shows a summary of final terrain attribute categories and their associated rates of landslide presence derived from Figure 2.
- The CHAID analysis splits the total sample population into subsets, and continues to split the subsets into smaller populations until no more significant splits can be done. To avoid splits that result in very small sample sizes, a minimum pop-

Table 8. Summary of terrain types and landslide rates for *>500 m^2 clearcut landslide presence* derived from Figure 2.

Type	Terrain Attributes	Landslide presence (%)
1	No gullies Maximum slope gradients 21 - 38° Upper or mid slope position	1
2	No gullies Maximum slope gradients 21 - 38° Lower or escarpment slope position Slope class from 20 - 30°	3
3	No gullies Maximum slope gradients 21 - 38° Lower or escarpment slope position Slope class from 31 – 35°	33
4	No gullies Maximum slope gradients >38° Mb+Mv or Mv terrain types	44
5	No gullies Maximum slope gradients >38° Terrain types other than listed in Type 4	8
6	Gullies <9 m deep	15
7	Gullies >9 m deep	58

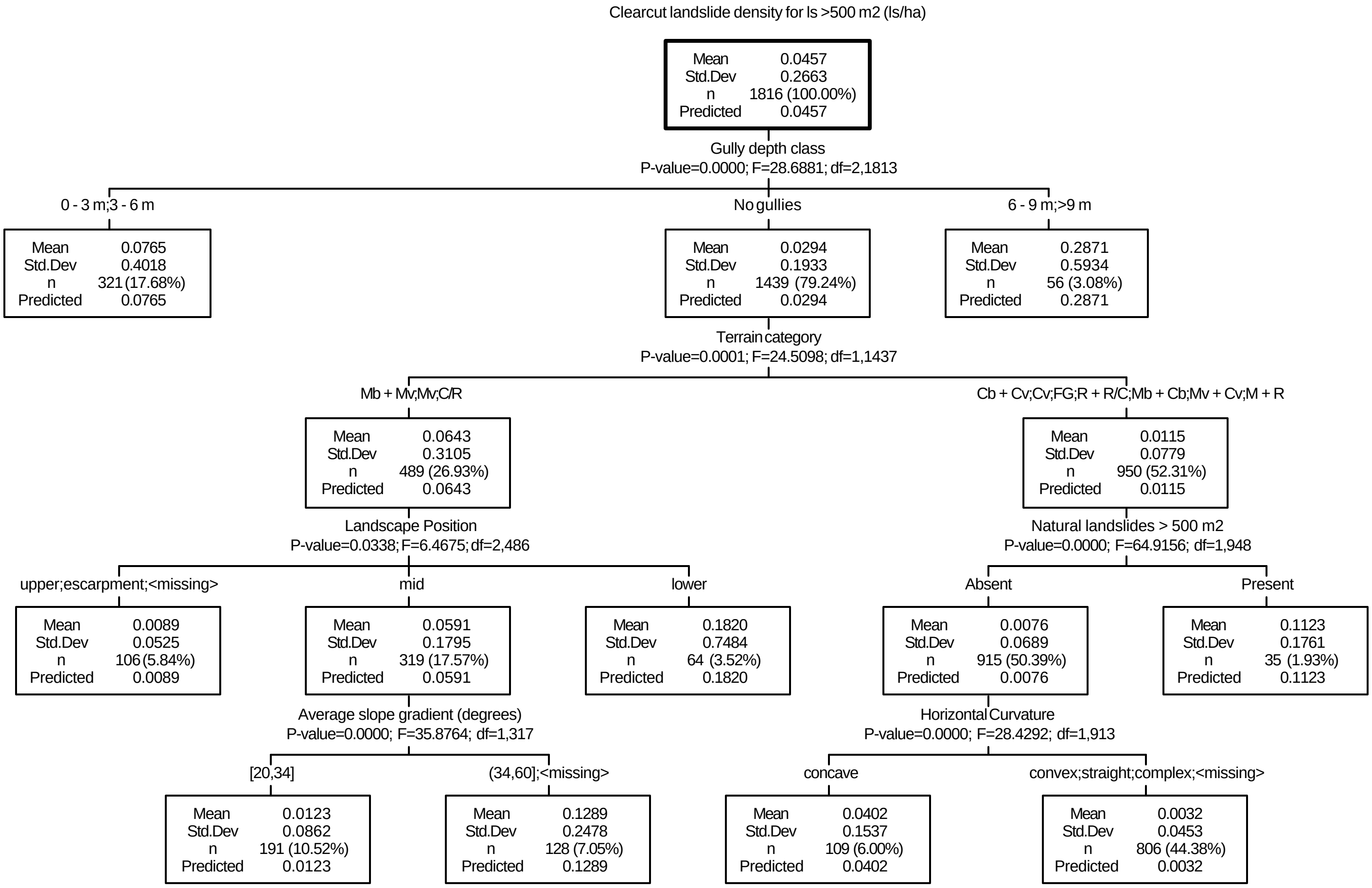

Figure 3. CHAID tree for *>500 m^2 clearcut landslide density (ls/ha)*.

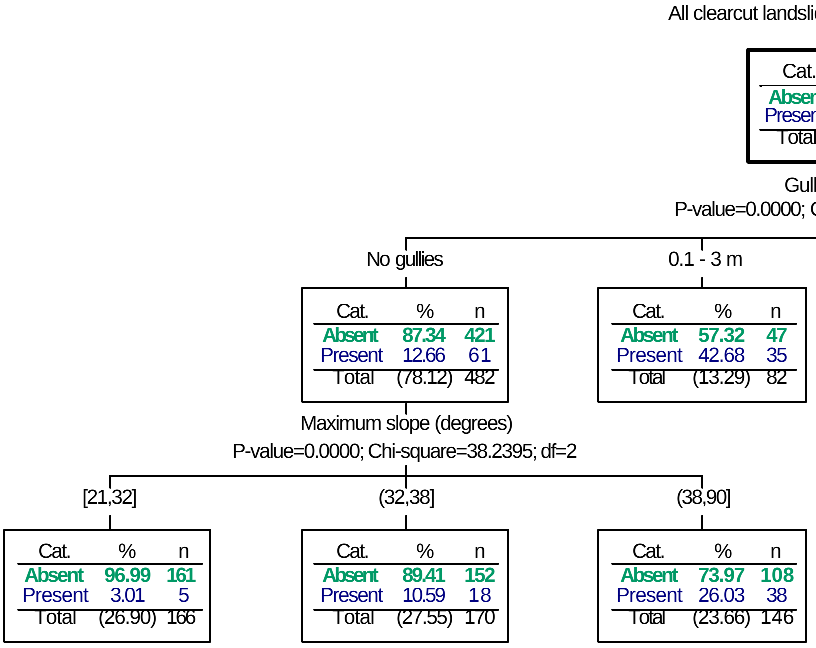

Figure 4. CHAID tree for *any size of clearcut landslide presence.*

ulation of 10 samples was imposed in the CHAID analysis. Readers should be aware that as sample size decreases, the error in the reported landslide presence or landslide density likely increases.

Figures 2, 3, and 4 show that clearcut landslide rates were strongly associated with gully depth, as all three CHAID analyses identified gully depth as the most significant terrain attribute. Other significant terrain attributes frequently present in the CHAID analyses of clearcut landslide rates include terrain category, landscape position, maximum slope gradient and presence of natural landslides.

Final terrain attribute categories for *>500 m^2 clearcut landslide presence* (Figure 2) ranged from just over 1% of polygons (as described above) to a high of 58% of polygons for gullies >9 m deep.

Final terrain attribute categories for *>500 m^2 clearcut landslide density* (Figure 3) show landslide rates from 0.003 ls/ha (lowest box in the right-hand corner of Figure 3) to 0.29 ls/ha (gullies >6 m deep). This is an important result, as it indicates that almost

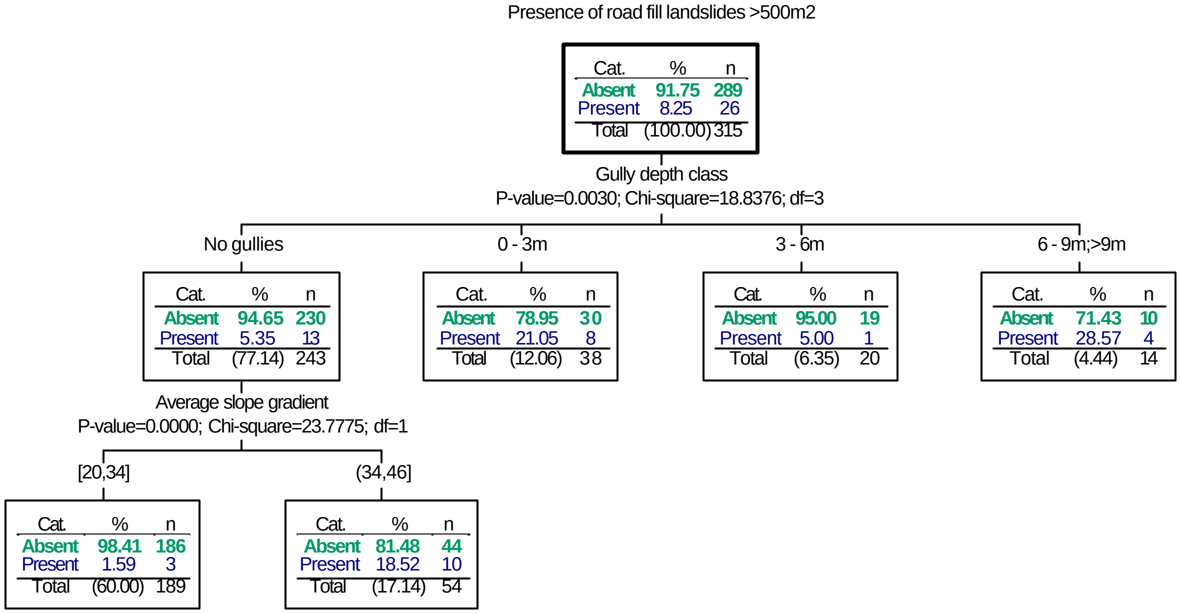

Figure 5. CHAID tree for *>500 m^2 road fill landslide presence.*

half of the study area (44%) had a landslide density of only 0.003 ls/ha – in other words, one post-logging landslide for about every 300 ha of logged terrain. Conversely, although gullies >6 m deep had about one post-logging landslide for every 3.5 ha of logged terrain, this type of terrain was fairly rare, representing only 3% of the study area.

Final terrain attribute categories for *any size of clearcut landslide presence* (Figure 4) ranged from 3% of polygons (lowest left box) to over 75% of polygons for gullies between 3 and 9 m deep.

CHAID analyses of road fill landslide rates are shown in Figures 5, 6 and 7. There was less consistency in significant terrain attributes for road fill landslide rates compared with clearcut landslide rates, but gully depth and average slope gradient were common to all three CHAID trees.

Final terrain attribute categories for *>500 m^2 road fill landslide presence* (Figure 5) ranged from 2% of the road segments (lowest left box) to 28% of the road segments for gullies >6 m deep. Most gullies had a greater rate of landslide presence than non-gullied slopes.

Final terrain attribute categories for *>500 m^2 road fill landslide density* ranged from 0.007 ls/100 m (lowest left box) to 0.47 ls/100 m for single gully slope morphology (Figure 6). Interpreting the lowest left box, road segments on uniform, benchy, or irregular slopes, without gullies, and with average slope gradients from 20° to ≤34° represented 59% of the road segments within the study, and had the lowest landslide density of all final terrain categories – an average of one >500 m^2 road fill landslide for about every 14 km of road length (0.007 ls/100 m).

Final terrain attribute categories for *any road fill landslide presence* (Figure 7) ranged from 20% of the road segments (lowest left box) to 49% of the road segments.

CHAID analyses of road cut landslide rates are shown in Figures 8, 9, and 10. Gully depth was a significant attribute for both *>500 m^2 road cut landslide presence* (Figure 8) and *>500 m^2 road cut landslide density* (Figure 9), and single gullies had a high percentage of samples with *any road cut landslide presence*. Average or maximum slope was a significant attribute for all three road cut landslide rates.

There were only three final terrain attribute categories for *>500 m^2 road cut landslide presence* (Figure 8), and these ranged from 1% of the road segments (lowest left box) to 29% of the road segments for gullies > 6 m deep.

Final terrain attribute categories for *>500 m^2 road cut landslide*

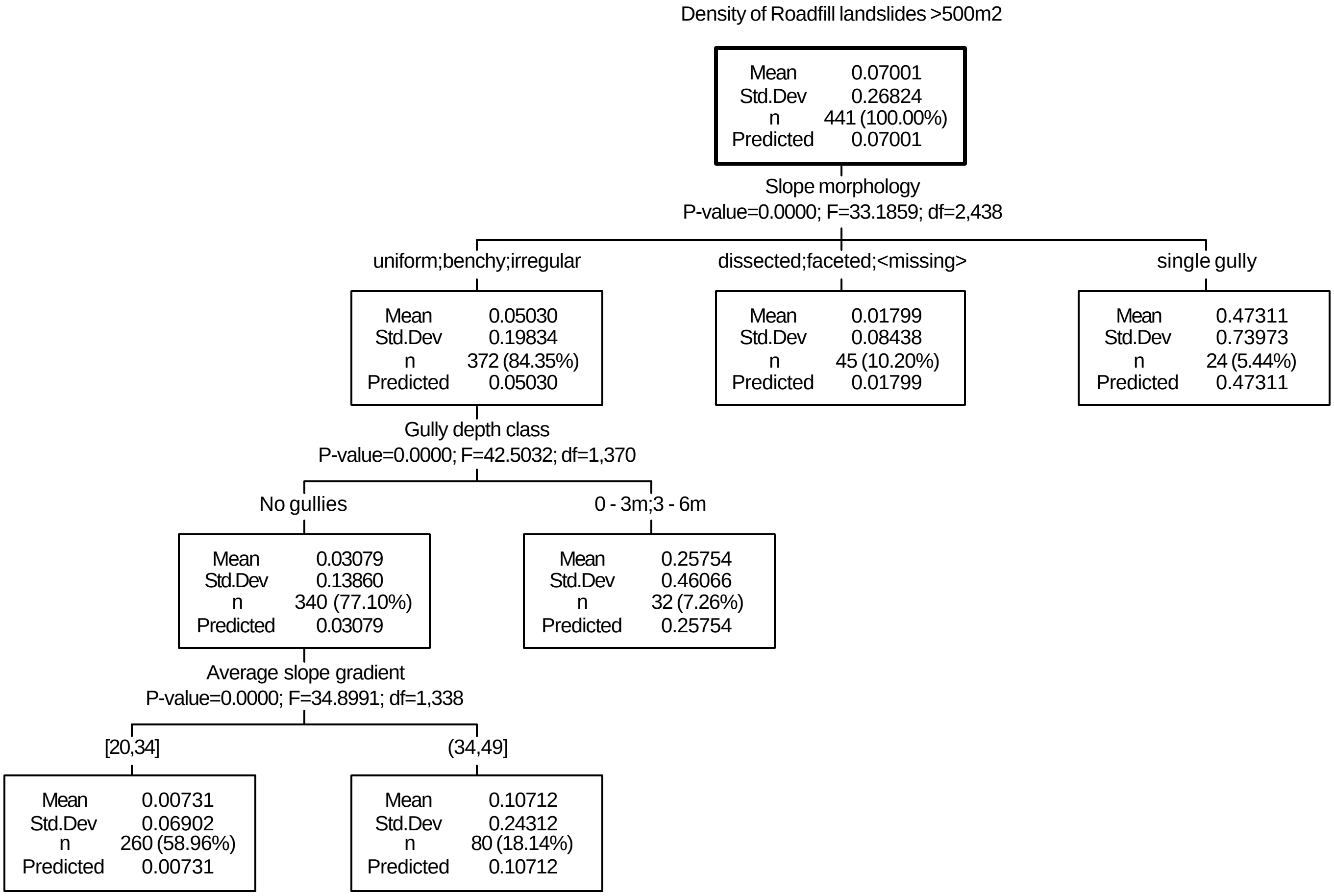

Figure 6. CHAID tree for *>500 m^2 road fill landslide density (ls/100 m).*

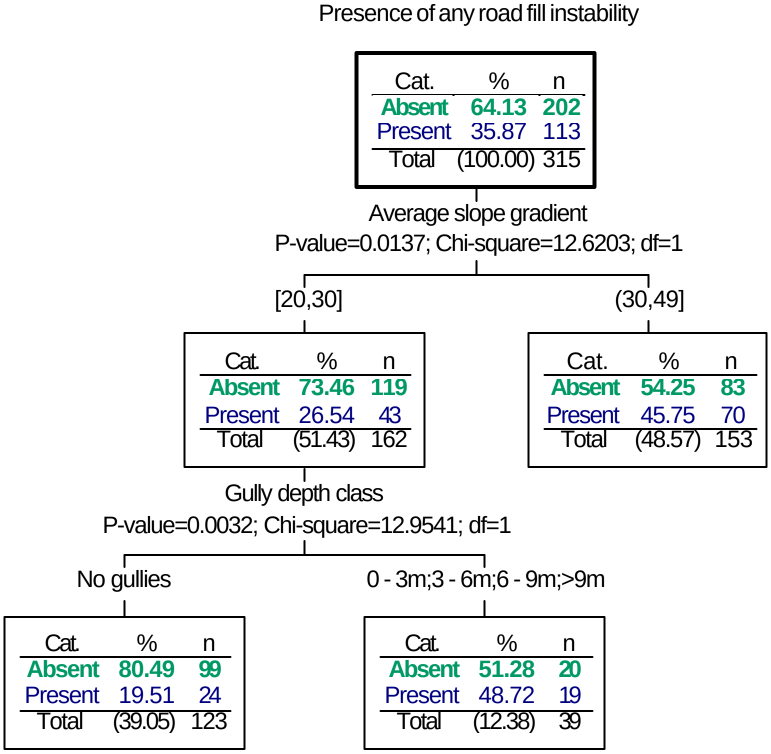

Figure 7. CHAID tree for *any road fill instability presence*.

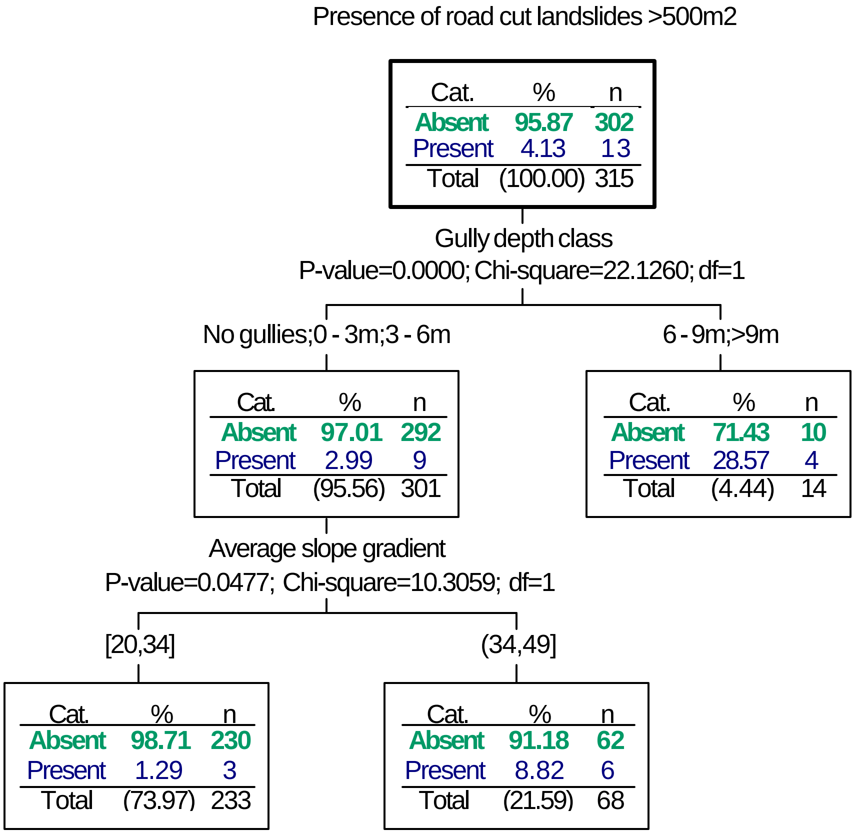

Figure 8. CHAID tree for *>500 m^2 road cut landslide presence*.

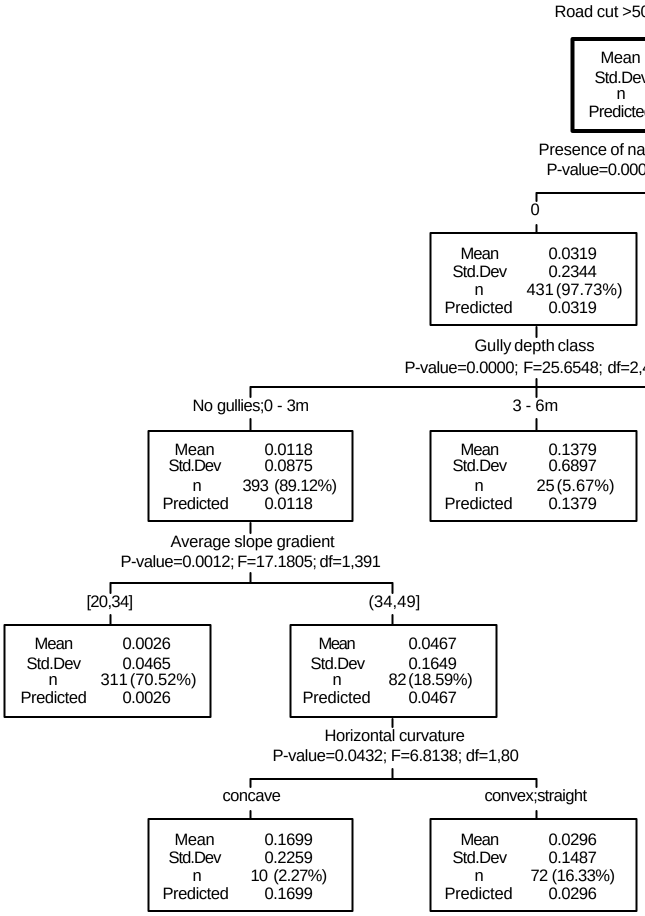

Figure 9. CHAID tree for *>500 m^2 road cut landslide density (ls/100 m)*.

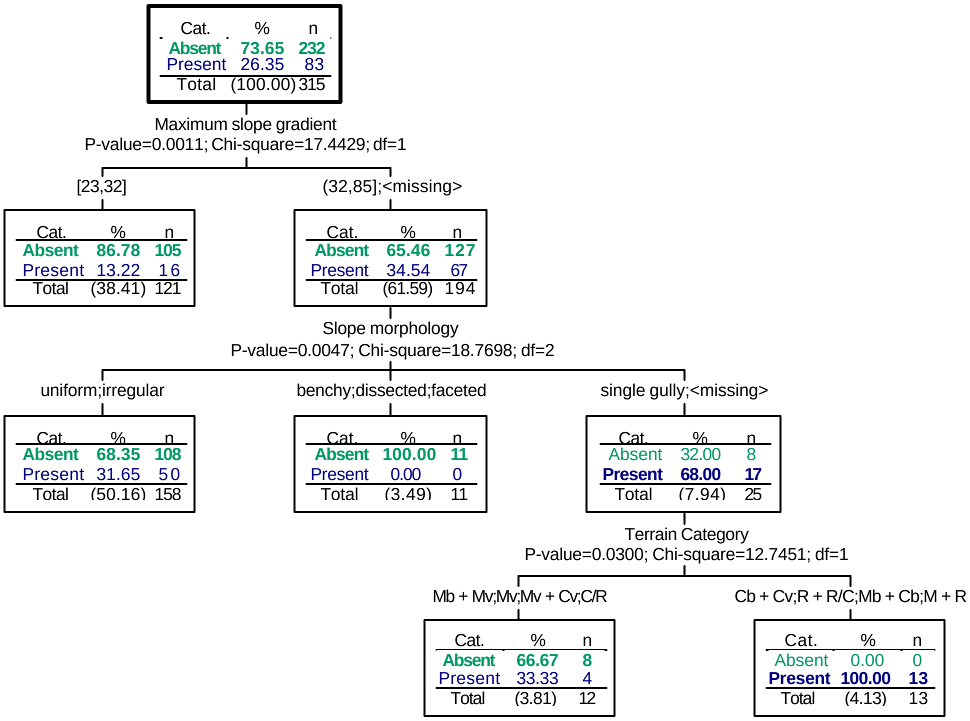

Figure 10. CHAID tree for *any road cut landslide presence*.

densities (Figure 9) ranged from 0.003 ls/100 m (left box, third level of analysis) to 0.67 ls/100 m for slopes that had >500 m^2 natural landslides present.

Final terrain attribute categories for *any road cut landslide presence* (Figure 10) ranged from 0% of the road segments (middle box, second level of analysis) to 100% of the road segments (right box, level 3)

5.0 DISCUSSION AND CONCLUSION

Based on the analyses in Section 4, there are a number of important terrain attributes that are consistently related to landslide rates (Table 9). There was a strong increase in clearcut, road fill, and road cut landslide rates as slope gradient increased. Clearcut landslide density did not show the pattern as clearly as other landslide rates did; however, when three small anomalous polygons are removed from the population, the effect is evident. The multivariate analyses examined the effect of minimum, maximum, and average slope gradient for each polygon. In some cases the CHAID analysis selected average slope gradient as the more significant variable compared to minimum or maximum slope gradient, but in other cases the maximum slope gradient was more significant. This finding suggests that both average slope gradient and maximum slope gradient are equally effective at predicting landslide likelihood.

The presence of gullies, and increasing gully depth, was almost always strongly associated with increasing landslide rates. The consistent identification of this attribute makes it an important criteria in predicting future post-logging landslide rates.

The presence of natural landslides was another effective indicator of high post-logging landslide rates. Polygons with natural landslides had about four to six times greater landslide rates than other polygons. There were only 11 polygons that had natural landslides, perhaps indicating a general tendency for those laying out areas for logging to avoid naturally unstable slopes.

Escarpment slopes and other lower landscape positions frequently showed elevated landslide rates. While escarpments are often recognized as potentially unstable areas, it is not clear why other lower landscape positions had higher landslide rates. It may be that the lower landscape positions are also locations of deep morainal deposits, a terrain type with a higher likelihood of landslides. In addition, lower slopes may also be wetter slopes, a condition often associated with increased landslide rates, although this is not evident in this study.

Deep morainal deposits and pure moraine veneers had elevated clearcut landslide rates compared with other terrain types (including moraine in combination with other terrain types). Interestingly, although moraine is often regarded as a more sensitive material than colluvium, other terrain attribute studies do not show this result (Rollerson, 1992; Rollerson et al, 1998; Rollerson et al, 2001; Rollerson et al, 2002). In many areas terrain units dominated by colluvial materials are often steeper than nearby morainal units. Consequently, slope gradient differences may mask differences in material strength.

Table 9. Summary of important terrain attributes

Type of landslide	Univariate analysis	Multivariate analysis
Clearcut	Significant terrain attributes: • presence of natural landslides • landscape position • slope morphology • horizontal curvature • terrain category • gully depth Less significant terrain attributes: • slope gradient	Most useful terrain attributes: • gully depth • terrain category • landscape position • maximum slope gradient • presence of natural landslides
Road Fill	Significant terrain attributes: • slope gradient Less significant terrain attributes • presence of natural landslides • landscape position • horizontal curvature • gully depth • slope aspect	Most useful terrain attributes: • gully depth • average slope gradient • slope morphology
Road Cut	Significant terrain attributes: • slope gradient • presence of natural landslides • landscape position • horizontal curvature • gully depth Less significant terrain attributes: • slope morphology • surficial material depth	Most useful terrain attributes: • gully depth • average slope gradient • presence of natural landslides

The average *>500 m^2 clearcut landslide density* in this study was 0.05 ls/ha. This is within the range of the average landslide densities from previous Coastal BC terrain attribute studies: from ≤0.01 ls/ha for the Coast Mountains (Rollerson et al, 2001), to about 0.24 ls/ha in the Queen Charlotte Islands (Rollerson, 1992). The Cascade Mountains had a slightly lower average *>500 m^2 clearcut landslide density* than was found on the west coast of Vancouver Island (0.06 ls/ha, Rollerson et al, 1998; Rollerson et al, 2002). Although the different bedrock types present in the Cascade Mountains rarely showed significance in this study, the higher landslide density present in the Cascade Mountains compared with the Coast Mountains suggests that bedrock geology exerts a notable regional effect when climatic regimes are similar. The granitic Coast Mountains likely produce surficial materials that are stronger than the surficial materials that are a product of the mixed geology of the Cascade Mountains.

The average *>500 m^2 road fill landslide density* for the Cascade Mountains was found to be 0.07 ls/100 m. Other terrain attribute studies found average road fill landslide densities ranging from 0.02 – 0.05 ls/100 m for the Coast Mountains, to 0.13 ls/100 m for the Queen Charlotte Islands. Again, the Cascade Mountains appear to be intermediate in landslide density compared with other areas of Coastal BC.

An important finding of this study is that post-logging landslides are not common on most of the terrain steeper than 20° in the Cascade Mountains. More than 60% of the terrain in this study had a *>500 m^2 clearcut landslide density* of ≤0.01 ls/ha.

Conversely, only about 15% of the terrain had >0.10 ls/ha. Successful identification of terrain subject to higher post-logging landslides will significantly reduce the number of logging-related landslides, but need not have a large effect on available timber supply. A similar situation occurs with roads, where the majority of road segments in steep terrain rarely have landslides. By identifying those terrain locations where road landslides may occur, road construction techniques that reduce the likelihood of landslides can be effectively employed where they are most needed.

Users of this study must be cautious in applying the results. The data were collected from specific locations in the Cascade Mountains, but may not be representative of all Cascade Mountain locations. In addition, study results can be affected by a few samples that are different from the norm. Consequently, simplistic application of the study results to unlogged locations may lead to significant errors. When making decisions based on these results, a person experienced in landslide and terrain assessment should be consulted.

If terrain stability assessment is to improve in British Columbia, then there is a need to communicate the expected likelihood of landslides more precisely than a simple qualitative evaluation of landslide likelihood. Terrain attributes such as slope gradient and the presence of gullies are consistent criteria that can be used to help predict landslide likelihood throughout Coastal British Columbia. Landslide rate data from regional and local terrain attribute studies can be used to replace overly simplistic and qualitative predictions of high, moderate, or low landslide likelihood.

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