Post-Logging Terrain Stability

In Clayoquot Sound and Barkley Sound

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ABSTRACT

Debris flows and other types of landslides are a common occurrence both naturally and following logging in Clayoquot Sound and Barkley Sound. Identifying terrain susceptible to landslides following logging and road building will be critical for ongoing forest management in the Clayoquot Sound/Barkley Sound area. An empirical approach, applied to a representative sample of logged hillslopes within a specific geographical area, is used to quantify the likelihood and frequency of post-logging landslide occurrence. For each map polygon within a sample area, terrain data including slope, slope morphology, surficial material, bedrock type, and the presence or absence of natural and post-logging landslides are recorded. Analysis of the data uses non-parametric univariate or multi-variate statistical tests to identify relationships between landslide frequency or likelihood and terrain features. In this report data collected from Clayoquot Sound and Barkley Sound is analyzed and relationships between terrain features and post-logging landslide occurrence are presented.

INTRODUCTION

In this report we focus on identifying landscapes vulnerable to landslides following logging in Clayoquot and Barkley Sounds. Unlike areas subject to natural landslide activity where there is often evidence of past landslide activity, in many of the areas where logging will take place there is no clear evidence of past instability as an indicator of possible post-logging landslide activity. As a consequence, data on terrain features other than natural instability must be utilized to develop predictive criteria to identify areas which may be subject to landslide initiation following logging or road building.

The method outlined in this report requires the collection of data on the frequency of landslides following logging and the characteristics of terrain susceptible to and not susceptible to post-logging slope failure, followed by the development of empirical criteria for terrain stability interpretations based on this data.Similar approaches were used for a small pilot study on the southwest coast of Vancouver Island (Rollerson and Sondheim 1985), the southern Coast Mountains (Howes 1987), and the Queen Charlotte Islands (QCI) (Rollerson 1992).

The approach, analysis and results presented in this report are part of a larger study which covers much of the northern and central west coast of Vancouver Island. The larger database includes study sites in Quatsino Sound, the Kyuquot peninsula and Nootka Island. For the purpose of developing criteria for terrain stability mapping specific to Clayoquot Sound, the existing data for Clayoquot Sound and the adjoining Barkley Sound study areas were extracted from the main

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database and augmented with an additional 299 samples collected from 2 new study areas in northern Clayoquot Sound.

OBJECTIVES

The objectives of this study are to:

- characterize steepland terrain types that are susceptible to landslides following forest harvesting (clearcutting) in Clayoquot and Barkley Sounds and those which are not.
- develop, for specific geographic areas, terrain-based stability classifications for Clayoquot and Barkley Sounds and surrounding areas that estimate the likelihood or frequency of landslide activity following forest harvesting.

STUDY AREAS

This report presents the analysis of a data set collected in the Clayoquot and Barkley Sounds. These areas are situated within the Vancouver Island Mountains along the central west coast of Vancouver Island. They are fairly representative of the range of climate and terrain present on the central west coast of Vancouver Island. This area is generally significantly wetter than the southern, central and eastern portions of the Vancouver Island Mountains.

Physical Setting

The study areas lie within the central portion of the Vancouver Island Mountains, a major northwest to southeast-trending physiographic unit that forms the core of Vancouver Island (Holland 1964). Elevations range from sea level to 2200 meters. Within the study areas the Vancouver Island Mountains can be subdivided into two sub-units consisting of the North Vancouver Island Ranges and the Vancouver Island Fiordland (Hoadley 1953; Yorath and Nasmith 1995).

The North Vancouver Island Ranges are 270 km long and 60 km wide, extending from Quatsino Sound in the north to Barkley Sound in the south. Topography tends to be rugged, surfaces being modified by Pleistocene glacial erosion resulting in a rounding of lower peaks and creation of steep U-shaped valley profiles (Howes 1981). Mid to upper valley side slopes tend to be mantled with shallow deposits of colluvium and till. Exposures of bedrock are common. In narrow valleys, these materials may extend to the valley floor. In wider valleys, lower slopes and valley floors tend to be mantled with thicker deposits of till, fluvioglacial, fluvial and debris flow materials.

Fiordland is 260 km long and 60 km wide, extending along the western portion of Vancouver Island from the Brooks Peninsula south to Barkley Sound. It includes both islands and peninsulas bounded by a network of fiords that penetrate inland from the exposed western coast. Within this sub-unit the land rises abruptly from the shoreline to elevations of 900 meters beyond which a more gradual slope leads to inland summits. Glaciation has rounded summit peaks, and these are usually completely forested (Howes 1981). Colluvial materials, bedrock outcrops and thin veneers of till tend to dominate on steep hillsides, ridges and summits. Till, fluvioglacial, fluvial and debris flow deposits predominate along gentle, lower hillsides and on valley floors in broader valleys.

The majority of the sampling areas for the current study in Clayoquot and Barkely Sound lie within the Fiordland physiographic sub-unit. In general landslide frequencies decrease from west to east across the island. Consequently, the results presented in this report will tend to overestimate expected post-logging landslide frequencies within the inland portions of the Vancouver Island Mountains.

Bedrock

In the Clayoquot Sound and Barkley Sound areas the dominant bedrock formations are the Karmutsen Formation basalts and andesites, the Vancouver Island Intrusions composed of quartz monzonite and granodiorite, and the Coast Plutonic Complex (CPC) diorites and amphibolites. Sicker Group meta-andesites and dacites are occasionally present (Roddick, Muller and Okulitch 1979).

Climate

The area is characterized by cool, wet winters and warm, moist summers. Mean annual precipitation increases from about 2900 mm at sea level on the outer west coast to greater than 4600 mm inland at sea level at the heads of inlets. Seventy to eighty percent of the precipitation occurs between October and March (Howes 1981). Snow is usually confined to higher elevations and is ephemeral at lower and mid elevations; the area is subject to occasional rain-on-snow events. The coastline is exposed to Pacific frontal storms of high intensity and long duration. Long-term precipitation records for coastal stations show three-day extreme totals with ten-year return periods ranging from 257 to 330 mm (Howes 1981). Limited short-term records from some unofficial inland stations show periods of significantly higher extreme rainfall. Wind data for the west coast of the Island is scarce, however, lighthouse station records (Cape Scott, Spring Island and Estevan) indicate maximum hourly speeds ranging from 60 to 120 km/hr. Greatest precipitation intensity/duration rain storms and highest wind velocities usually occur during the winter months (October to March). Rainstorms of sufficient magnitude to initiate debris flows usually occur several times every year and may not be confined to the winter period.

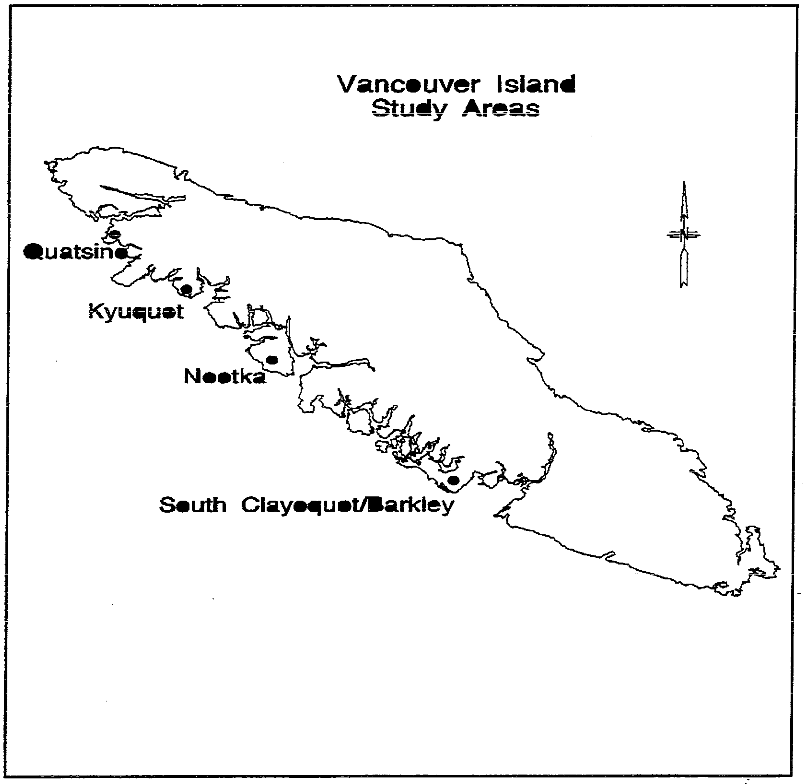
METHODOLOGY

Sampling Design

A number of representative areas were selected for study within the Clayoquot/Barkley Sound area. Within each study area, all accessible logged areas ranging in age from 6 to 15 years following harvesting were selected for study. The lower age limit was imposed to ensure that the study areas have experienced a number of large storms and to give time for loss in root strength to occur. The upper age limit was imposed because crown closure and increasing tree height in the regenerating plantations tends to mask local terrain features including small landslides, making collection of accurate data difficult. We have observed a number of situations where rapidly growing conifers and hardwoods can completely mask the presence of individual landslides in clearcut areas within 10 to 15 years.

Each selected area was mapped at a scale of 1:20,000 using the BC Terrain Classification System (Howes and Kenk 1988), 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 constitutes a single sample.

Figure 1. Study Area Location Map



The data set currently consists of a total of 1194 terrain polygons, representing an aggregate area of approximately 4812 hectares. The mean polygon area is 4.1 hectares, with a standard deviation of 3.2 hectares and a range of 0.3 to 38.8 hectares. Over time this data set will be augmented by additional sampling within the main study areas. Updating landslide incidence will occur periodically, usually after major storm events or when new aerial photography is flown. At any point in time, the data set will slightly under represent the total number of post-logging landslides which 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 feature data to be collected and by having the mappers work together with a mapping coordinator to ensure a consistent approach. The analysis of categorical terrain data involves the grouping of a large number of distinct terrain types into a smaller set of more generalized terrain categories. This consolidation reduces the effect of differences in terrain polygon delineation and classification.

Data Collection

For each map polygon, terrain feature data such as landscape position, slope, aspect, slope morphology, slope curvature, soil drainage class, surficial material, bedrock type, and the presence or absence of natural and post-logging landslides was recorded. For estimating post-logging landslide frequency, landslides smaller than 0.05 hectares were excluded because they could not be reliably identified at the air photo scales used. Landslides identified in the field or on aerial photography that were 0.05 hectares and larger are recorded.

Data Analysis

Non-parametric statistical tests (Table 1) were applied to identify relationships between landslide frequency and individual terrain features. Individual terrain polygons were then grouped into a limited number of multi-factor terrain categories having a similar likelihood of post-logging failure using CHAID (Chi-squared Automatic Interaction Detector). CHAID is a relatively new, 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. Both dependent and predictor variables are treated as categorical variables. The procedure merges categories of a predictor variable that are not significantly different at each segmentation level. The analysis produces an easy-to-read tree diagram (Figure 2) that identifies the defining variables and presents statistics for each separate group or segment of the dependent variable. These categories can then form the basis of a terrain stability classification which estimates the likelihood of landslides occurring after forest harvesting. CHAID was first used in BC for this purpose by Pack (1995) in a study of landslides related to logging roads in the interior of the province.

RESULTS AND DISCUSSION

Eighty-five percent of the 1194 sample terrain polygons in the data set remained stable after logging. By comparison, 78 percent of the 760 samples in a data set from the QCI (Rollerson 1992) remained stable for the same 6 to 15-year period after logging. The overall mean post-logging landslide frequency for the study area was 0.06 landslides per hectare, contrasting sharply with a overall mean landslide frequency of 0.17 landslides per hectare for areas of similar terrain in the QCI and 0.08 landslides per hectare for the larger data set representing the central and northern west coast of Vancouver Island (Rollerson, et al, 1997).

Post-logging landslide frequencies show a statistically significant relationship at the 0.00 level for 7 out of the 14 terrain variables analyzed (Table 1), another 5 are significant at the 0.01 to 0.05 levels of significance. As we have seen elsewhere (Rollerson 1992, Rollerson and Sondheim 1985), increases in landslide frequency on a per hectare basis tend to correspond with an increase in the percentage of polygons (cases) within a group or class that experience failure (Table 2). In a general sense, the percentage of cases experiencing failure can be interpreted as a qualitative measure or ranking of the likelihood or probability, of landslide activity following logging on similar terrain in the same climatic region. Because the actual sample polygons vary in number, size and character somewhat, we remain uncertain how precise this statistic is as a measure of probability.

Groupings of average polygon slope angle show a trend of increasing landslide frequency with increasing slope angle up to approximately 46 degrees, when landslide frequency decreases while the actual percentage of polygons experiencing failure begins to drop off at about 40 degrees (Table 2). These lower values are likely explained by the increasing dominance of bedrock and the relatively limited and discontinuous character of surficial materials on these steeper slopes. The highest landslide frequencies and percentage of samples experiencing failure are associated with those terrain polygons with slope gradients in the 30 to 40 degree range.

The presence of natural landslides shows a positive association with post-logging landslide activity; some of the highest post-logging landslide frequencies are associated with these features.

Steep stream escarpments and headwater drainage areas are associated with fairly high landslide frequencies, as are areas of highly dissected terrain (frequent gullies) or larger individual gullies (gullies that are large enough to map as distinct terrain polygons). Crosstabulation analysis shows that about half the headwater drainage areas are either dissected or are the headward zones of individual large gullies. About one third of the areas identified as stream escarpments form the side walls of large gullies, the rest of the stream escarpments are classified as uniform terrain. In other areas, these escarpments can be highly dissected and imperfectly drained.

Differences in landslide frequencies associated with varying surficial materials (terrain categories) are not great; however, cross-tabulation shows a fair degree of correspondence between different terrain categories and slope class. For example, till, which one would expect to be less stable than angular, bedrock-derived colluvium, tends to be associated with a gentler range slope angles than colluvium.

Horizontal slope curvature shows higher failure frequencies associated with concave and complex slopes than with convex and straight slopes. Typically gullied areas and headwater drainage areas have a concave curvature along the horizontal plane.

Soil drainage shows reasonable correspondence with failure frequency. Failure frequencies decrease as the soils become more rapidly drained.

There is no strong association with aspect when aspect is evaluated based on traditional cardinal directions expressed as octants (e.g., NNE, SSW, etc.). However, when aspect is expressed as exposure to north versus south aspects the relationship between landslide frequency and aspect is significant. The relationship can be further refined by combining octants experiencing similar landslide frequencies (Tables 1 and 2). In this area, storms from the southeast or southwest are more common than storms from more northerly aspects this finding suggests that small, hillside-specific rain shadows may affect landslide frequency on south-facing versus north-facing slopes. Another possible explanation for this relationship is that there is structural control over slope gradient that corresponds to certain cardinal directions. Crosstabulation analysis showed no significant difference between slope gradients and the 8 cardinal directions or any of the other combinations of aspect noted above.

Bedrock formation does not show a statistically significant association with failure frequency; however, lithology, structure and competence do. Unlike bedrock formation which was observed or inferred at every polygon, lithology, structure and competence were only recorded where bedrock was exposed at the ground surface or in road cuts, typically areas of shallow overburden. These are the very situations where we might expect to see stronger bedrock control over soil physical properties or local stability conditions. For example bedrock shear zones often control gully location and associated landslide activity.

As would be expected, CHAID (Figure 2) shows similar trends to the univariate analysis. Slope angle is the most significant predictor variable used to separate stable from unstable terrain. Slope gradient is followed closely by slope morphology and slope curvature resulting in further separation of stable from unstable terrain. At the lowest level in the classification tree aspect and bedrock competence are significant predictor variables. However these final splits do not result in any practical improvement in the segregation of stable from unstable terrain units. Not surprisingly, the correspondence between slope gradient and terrain category (surficial material combinations) means that terrain category is not used as a predictor variable by CHAID, even though we expect that variation in physical properties between materials will have an effect on post-logging landslide frequencies.

The CHAID analysis results in a reasonable although not wholly satisfactory separation of stable from unstable terrain. In part this occurs because of a limited number of samples for some significant predictor variables. The rules set for allowable numbers of samples in a group before splitting of the group can occur prevents the creation of very small sub-groups.

Figure 3 presents a similar CHAID tree resulting from analysis of the larger database for the northern and central west coast of Vancouver Island. In general that analysis used similar variables to separate stable from unstable terrain, although not in quite the same combinations and sequences. Similarly a comparision with the univariate analysis for the larger database (Rollerson, et al., 1997) with the univariate analysis of the Clayoquot/Barkely database shows very similar trends. This correspondence suggests that the relationships between terrain attributes and post-logging stability conditions will, within limits and subject to unique local conditions be fairly similar along the west coast of the island from Barkely Sound to Quatsino Sound.

SUMMARY

Comparison with the results of this study to work elsewhere (Rollerson, 1992) and unpulished data from a companion study in the Coast Mountains shows a number of similar trends:

In the rare cases where we log terrain where evidence of natural landslide activity is present there is a moderate to high likelihood of post-logging failures.

Terrain units dominated by lacustrine, glaciolacustrine, marine and glaciomarine materials though relatively rare tend to be the least stable, landforms dominated by till and some glaciofluvial areas are intermediate and terrain dominated by colluvial materials and bedrock tends to be most stable.

Typically gullied or highly dissected terrain is more vulnerable to post-logging landslide activity than uniform terrain. Irregular surfaces and benchy terrain tend to be the most stable.

We rarely see any obvious relationship between slope position and landslide activity. However if selected landscape units are considered then one or two exceptions are obvious. Headwater drainage basins (1st or "zero" order basins, often the headward portion of large gully or hillslope stream channel systems) frequently show a high incidence of landslide activity. In a similar fashion, steep, often imperfectly drained stream escarpments exhibit high post-logging landslide activity.

We often see slightly higher or significantly higher landslide frequencies associated with concave slopes compared to convex and straight slopes. These concave slopes are often associated with gully systems or headwater drainage areas.

Higher landslide frequencies are associated with weaker bedrock types (e.g. argillites, shales) as compared to stronger bedrock types (competent intrusives and volcanics). Often highly sheared or very highly fractured rocks are associated with higher landslide activity than massive or weakly fractured rocks. Shear or fracture zones are often found at the initiation point of shallow translational landslides where they control the location of ground water discharge at the soil/rock interface.

The general trend is for landslide frequency to increase as soil drainage conditions change from rapidly drained though well drained to imperfectly and poorly drained, other factors such as slope angle and surficial materials being held constant. Consequently, certain soil morphological characteristics (dull grey or low chroma colours, mottles, build-up of humic materials) and other indications of seasonally high water tables or impeded drainage (wet site vegetation, shallow rooting) can give an indication of expected post-logging stability conditions.

In general slope aspect is not associated with variation in the incidence of post-logging landslide activity. However, our work on the west coast of Vancouver Island suggests that there are some significant differences between different slope orientations. In this study for example, slopes exposed to the dominant SE and SW storm paths experience higher landslide activity.

Changes in climate and differences in the distribution and character of surficial materials, bedrock, slope morphology and other factors can result in quite different landslide frequencies and terrain/landslide relationships among different physiographic or geographic regions. Extrapolation of results from one area to another must be done with extreme caution.

Table 1. Comparison of terrain features with post-harvesting landslide frequency

	Significance Level	
Variable	**Kruskal-Wallis(1)**	**Chi-square(2)**
Slope class	.0000	.00000
Natural landslides	.0000	.02168
Minor natural landslides	.0126	.00314
Landscape position	.0024	.00000
Slope morphology	.0000	.00000
Horizontal curvature	.0038	.02515
Soil drainage	.0043	.00647
Slope aspect	.0535	.05487
North vs south aspect	.0000	.00301
"Combined octants"	.0066	.00818
Elevation	.0208	.02016
Terrain category	.2425	.23134
Bedrock formation	.5036	.53741
Bedrock lithology	.0255	.05142
Bedrock structure	.0489	.05237
Bedrock competence	.0104	.01580

(1) based on post-logging clearcut landslide frequency (number/ha).
(2) based on presence or absence of post-logging clearcut landslides.

Table 2. Terrain Features - Clearcut Landslides Summary Statistics

Variable	Code	n	Mean landslide frequency (#/ha)	Percent units failing
Slope class (°)				
15-19	1	35	.00	0.0
20-25	2	277	.02	3.6
26-30	3	243	.05	13.6
31-35	4	367	.10	24.0
36-40	5	175	.07	21.1
41-46	6	51	.07	13.7
>46	7	32	.02	6.3
Natural landslides				
absent	A	1168	.06	14.6
present	P	26	.19	30.8
Minor natural landslides				
absent	A	1180	.06	14.6
present	P	14	.19	42.9
Landscape position				
apex	A	12	.08	8.3
upper slope	U	397	.06	15.1
mid slope	M	628	.06	14.3
lower slope	L	117	.05	6.8
stream escarpment	E	8	.26	25.0
headwater basin	H	31	.20	54.8
Slope morphology				
uniform	U	776	.06	14.8
benchy	B	32	.00	3.1
dissected	D	67	.13	37.3
faceted	F	16	.01	6.3
irregular	I	221	.03	6.8
single gullies	S	81	.18	25.9
Terrain category				
Morainal (till)	1	600	.07	15.8
Colluvial	2	75	.05	17.3
Fluvioglacial	3	4	—	—
Marine	4	3	—	—
Rock	5	5	—	—
Morainal+colluvial	6	179	.06	17.3
Morainal+fluvioglacial	7	4	.03	—
Morainal/rock	8	202	.07	14.9
Colluvial/rock	9	49	.03	8.2
Rock/colluvial (1)	a	73	.01	4.1
Horizontal curvature				
concave	1	316	.09	20.3
convex	2	291	.05	11.7
straight	3	566	.05	13.4
complex	4	14	.09	21.4
Soil drainage				
rapidly	r	162	.03	7.4
well	w	908	.06	16.1
moderately well	m	119	.08	15.1
imperfectly	I	2	—	—
poorly	p	1	—	—

(1) proportion symbols: / = dominant/subdominant;
+ = either component may be dominant or they may be equivalent.

continued

Table 2 (continued)

Variable	Code	n	Mean (#/ha)	% Failing
Slope aspect				
NNE	1	86	.03	8.1
ENE	2	100	.04	10.0
ESE	3	190	.07	17.4
SSE	4	219	.08	20.1
SSW	5	87	.09	19.5
WSW	6	160	.08	14.4
WNW	7	192	.05	14.6
NNW	8	147	.04	10.9
North vs south aspect				
North	1	525	.04	11.6
South	2	656	.08	17.8
"Combined octants"				
NNW-NNE	1	233	.03	9.9
WNW+ENE	2	292	.05	13.0
WSW+ESE	3	350	.07	16.0
SSW-SSE	4	306	.08	19.9
Elevation (m)				
100	1	18	.02	5.6
101-200	2	74	.04	6.8
201-300	3	137	.06	13.9
301-400	4	175	.06	13.1
401-500	5	221	.07	18.6
501-600	6	267	.09	20.2
601-700	7	176	.04	13.1
700	8	120	.03	10.0
Bedrock formation				
VII / CPC	1	735	.07	15.0
Bonanza	2	6	—	—
Karmutsen	3	352	.05	15.9
Quatsino	4	28	.02	7.1
Sicker	5	6	—	—
Bedrock lithology				
quartz monzonite	2	278	.10	20.9
granodiorite	4	85	.04	14.1
diorite	6	189	.03	10.1
andesite	15	61	.03	11.5
basalt	17	175	.04	13.1
volcanic breccia	19	21	.08	13.1
gneiss	30	5	—	—
greywacke	53	12	.04	16.7
limestone	58	29	.02	10.3
Bedrock structure				
massive	1	154	.03	9.7
fractured	2	331	.06	17.7
sheared	3	22	.13	27.3
bedded	4	2	—	—
Bedrock competence				
high	1	335	.04	12.2
moderate	2	104	.08	19.2
low	3	31	.11	29.0

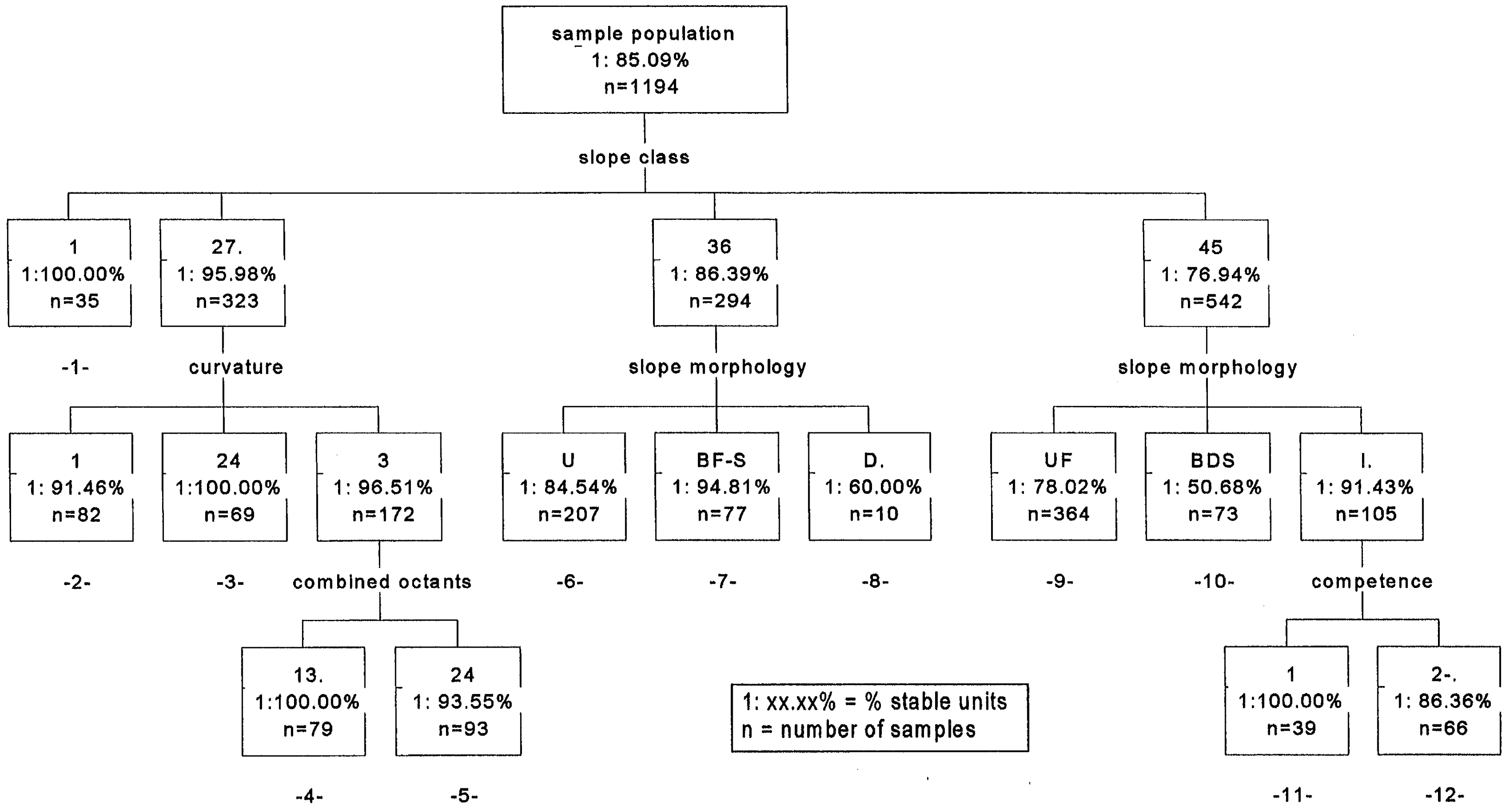


Figure 2. CHAID tree for Clayoquot Sound/Barkley Sound study area

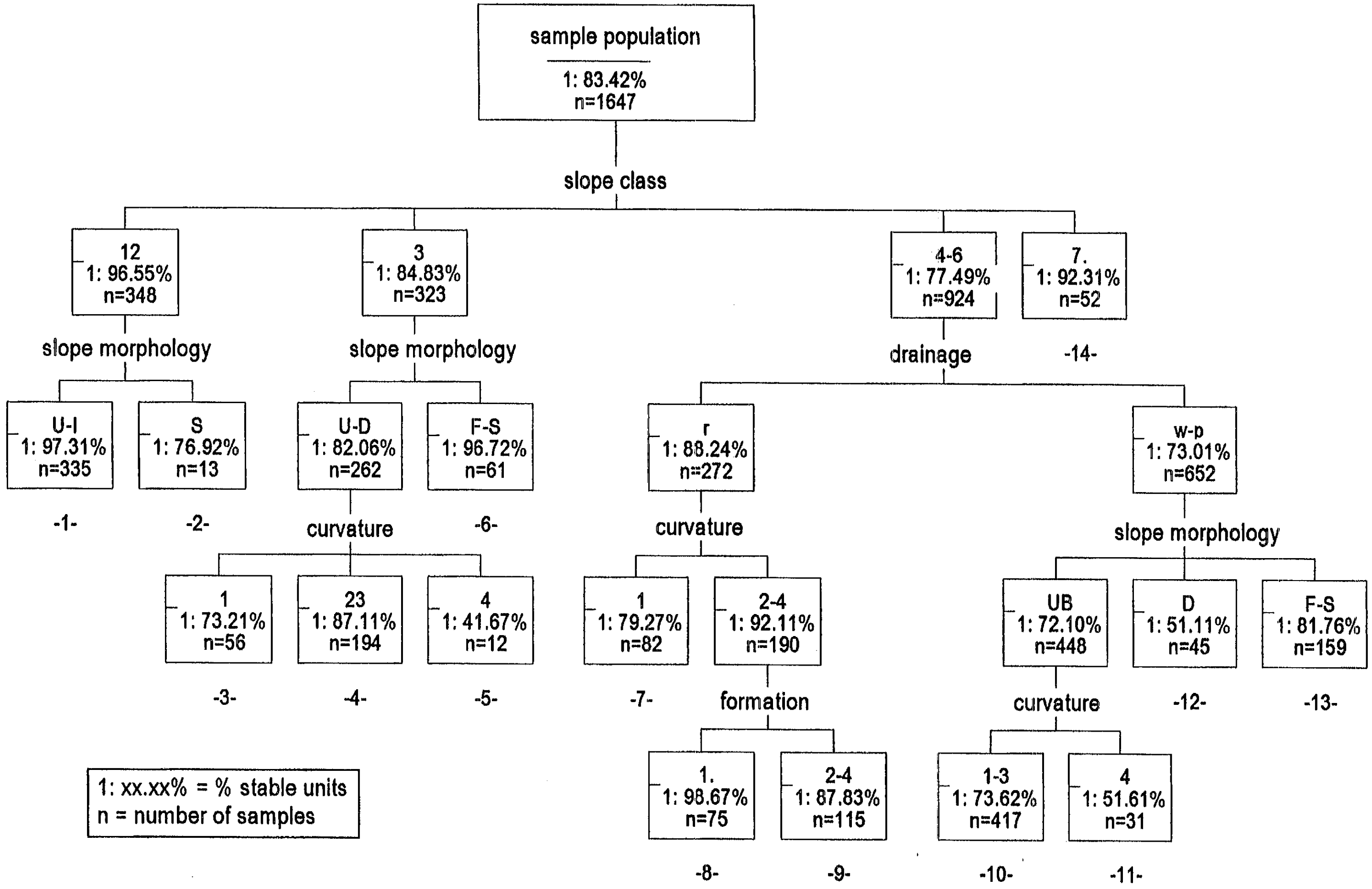


Figure 3. CHAID tree for the central and northern west coast of Vancouver Island

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